Effects of Variations in Incident Heat Flux When Using Cone Calorimeter Test Data for Prediction of Full-Scale Heat Release Rates of Polyurethane Foam

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Abstract: The development of methods to predict full-scale fire behaviour using small-scale test data is of great interest to the fire community. This study evaluated the ability of one model, originally developed during the European Combustion Behaviour of Upholstered Furniture (CBUF) project, to predict heat release rates. Polyurethane foam specimens were tested in the furniture calorimeter using both centre and edge ignition locations. Input data was obtained using cone calorimeter tests and infrared video-based flame area measurements. Two particular issues were investigated: how variations in incident heat flux in cone calorimeter tests impact heat release rate predictions, and the ability of the model to predict results for different foam thicknesses. Heat release rate predictions showed good agreement with experimental results, particularly during the growth phase of the fire. The model was more successful in predicting results for edge ignition tests than for centre ignition tests, and in predicting results for thinner foams. Results indicated that, due to sensitivity of the burning behaviour to foam specimen geometry and ignition location, a single incident heat flux could not be specified for generating input for the CBUF model. Potential methods to determine appropriate cone calorimeter input for various geometries and ignition locations are discussed.

Keywords: furniture calorimeter, fire testing, cone calorimeter, fire modeling, scaling, polyurethane foam

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1. INTRODUCTION

A relatively large number of people are injured or killed each year in fires that begin with the ignition of mattresses or upholstered furniture. For example, National Fire Protection Association statistics indicate that from 2002 to 2005, an average of 378 people were killed each year in the U.S. as a result of fires that began with the ignition of a mattress or bedding [1]. Fires involving mattresses and upholstered furniture can grow rapidly, and result in large heat release rates and the release of large total amounts of energy. A key component in most furniture and mattresses is polyurethane foam. Therefore, it is important to understand the fire behaviour of this foam when evaluating the fire performance of complete products that contain this material.

Traditionally the fire behaviour of residential mattresses has been evaluated using smouldering ignition sources, such as a cigarette, in small (e.g., CAN-CGSB 4.2 No. 27.7 [2]) or full-scale fire tests (e.g., CFR 1632 [3]). However, new tests, which can be used to evaluate the fire behaviour of residential mattresses, have been in place in Canada (CAN/ULC-S137 [4]) and the United States (CFR 1633 [5]) since 2006. These tests are designed to evaluate the performance of mattresses when ignited using an open flame ignition source, such as a candle or a set of bedclothes that were previously ignited. Other open-flame tests have been used for a longer period of time to evaluate mattresses for use in other occupancies, such as prisons (e.g., CA TB 121 [6]) or dormitories (CA TB 129 [7]). A review of the development of mattress fire tests can be found in [8].

When regulated on the basis of open flame test results, mattresses must pass various criteria based on values of heat release rate, total heat release and mass loss rate that fall below maximum values over a given time period. Many standards allow the provision of testing a mattress in either an open furniture calorimeter or in a test room of a particular size. For mattresses tested in a room configuration, additional measurements may involve determination of maximum temperatures and carbon monoxide concentrations in the hot ceiling gases [6], or whether a test room reaches flashover within a specified time period [9].

As these tests, like most full-scale fire tests, are expensive, and there are limited test facilities able to accommodate such tests, there is a need to develop methods to evaluate the fire behaviour of mattresses using small-scale tests, especially during the design process. As mentioned earlier, small-scale tests with smouldering ignition sources have been used in Canada [2] to regulate fire performance of residential mattresses. Other examples of small-scale tests include cone calorimeter tests of a mattress mock-up or of the individual components in a mattress assembly (ASTM E 1474 [10]). Small-scale tests are more cost-effective than full-scale tests and therefore can be used to effectively screen new materials and designs. However, it is currently very difficult to accurately predict full-scale fire behaviour of a mattress based solely on small-scale test results. Therefore, to more fully utilize small-scale testing, methods must be developed to accurately predict full-scale fire test results and real world fire behaviour using small-scale test data. This is particularly important for mattresses, since changes are regularly made to the design of mattresses and the materials used to manufacture these products.

The University of Saskatchewan (UofS) and Waterloo (UW) fire research groups have evaluated a number of scaling models which may be used to predict full-scale fire test results of mattresses using cone calorimeter test data. In the first study, fire protection engineering correlations were used to predict temperatures measured in three inner-spring mattress fires in a 3.6 m by 4.2 m by 2.7 m high room, conducted as part of a field fire test program in a former office building [11]. Cone calorimeter tests of specimens taken from the three mattresses were used to select t^2 design fire models [12]. These t^2 fires were then used to predict temperatures in the test room using Alpert's ceiling jet correlation [13]. As indicated in Figure 1, predicted temperatures were found to be reasonably close to those measured in the test rooms. One major source of error was the fact that the correlations used to estimate the temperature assumed that the fire was stationary, while in the actual tests, flames spread across the mattresses.

Another major source of error was the uncertainty in predicting the time-dependent heat release rates of each fire. As heat release rates could not be measured in the field, values were estimated using the t^2 fire models. Therefore, methods to predict full-scale heat release rates using cone calorimeter data were investigated in a subsequent study [14]. To overcome the difficulties associated with modelling complete inner-spring mattresses, 10 cm thick polyurethane foam specimens, with nominal dimensions of 0.6 m by 0.6 m, 0.6 m by 1.2 m, and 1.2 m by 1.2 m, were tested in the furniture calorimeter. Specimens were ignited in the centre or in the middle of one edge of the foam. Cone calorimeter specimens of the same foams were tested using an incident heat flux of 35 kW/m^2.

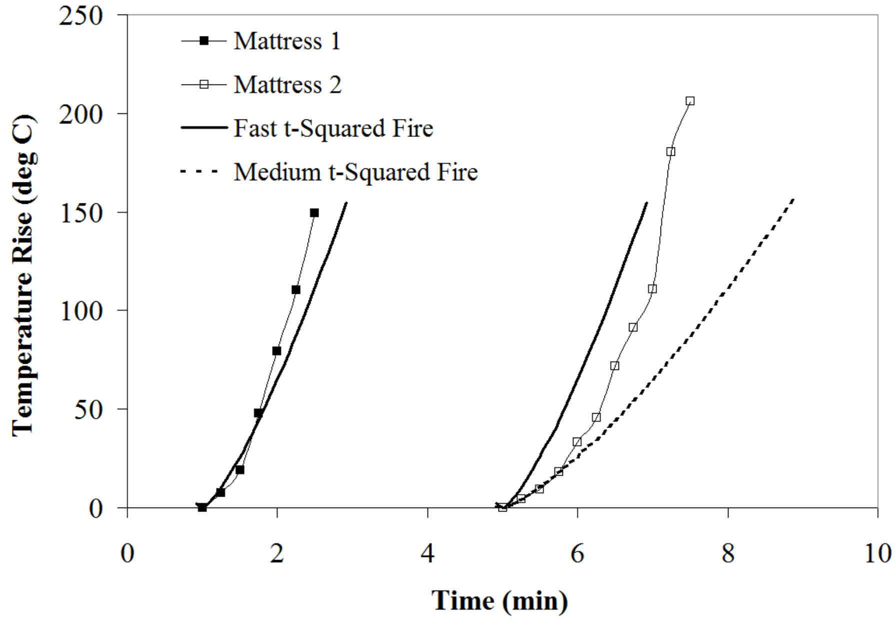


Figure 1. Comparison of Ceiling Temperatures at One Location Measured During Field Fire Tests of Two Mattresses and Predicted Using Two t^2 Fires [11].

Heat release rates measured in the furniture calorimeter tests were compared with those predicted using common t^2 fire models. For centre ignition tests, shown in Figure 2, measured heat release rates were between those predicted using medium and fast t^2 fires. Not shown here, for edge ignition tests, measured heat release rates lay between those predicted using slow to medium t^2 fires. These results demonstrate that t^2 fire models could be used to predict full-scale heat release rates, but a method must first be found to determine the appropriate t^2 fire model to use for a particular size of foam/ignition location combination.

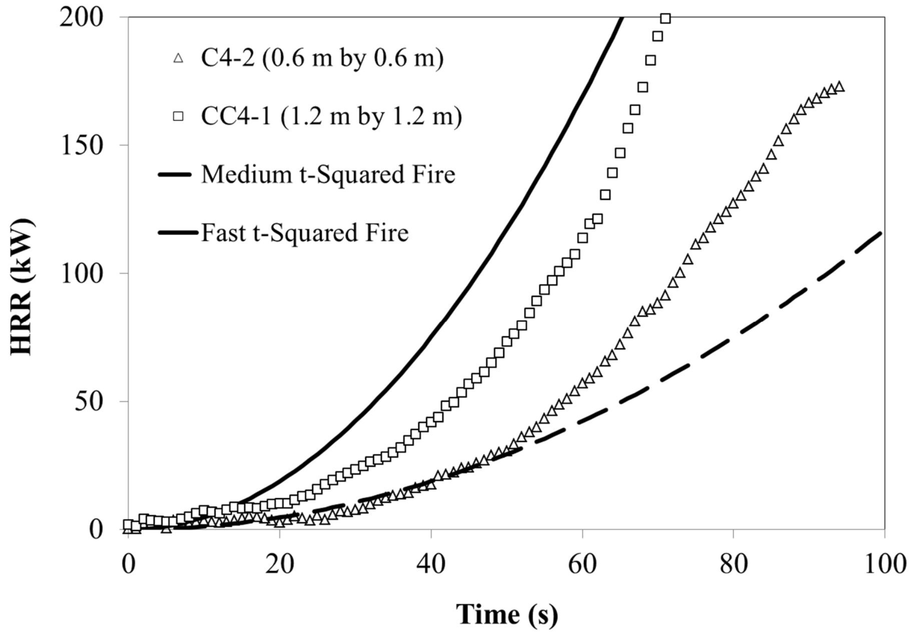


Figure 2. Comparison of Heat Release Rates Predicted Using Two t^2 Fires and Measured During Furniture Calorimeter Tests of Two 10 cm Thick Pieces of Polyurethane Foam Ignited in the Centre [14].

The second model that was evaluated in this study was one of three models for the full-scale fire behaviour of mattresses and upholstered furniture developed during the European Combustion Behaviour of Upholstered Furniture (CBUF) project in the 1990's [15]. This model predicts full-scale heat release rates (Q(t)) from a burning item using the convolution integral of the rate of change of the burning area ($A_f(t)$), and the heat release rate density (q"(t)) measured during a cone calorimeter test of a specimen of the material via the following equation:

$$Q(t) = \int_0^t q''(t-\tau)\frac{dA_f(\tau)}{d\tau}d\tau \tag{1}$$

where τ is a dummy variable. The model is based on the assumption that the heat release rate curve for each 10 cm by 10 cm portion of a full-scale specimen will be the same as the heat release rate curve for a 10 cm by 10 cm specimen of the material tested in the cone calorimeter. This model is based on models originally developed by Wickstrom and Goransson to predict the fire behaviour of lining materials in room corner fire tests [16,17].

Heat release rate density measurements for the foam were made using cone calorimeter tests conducted using an incident heat flux of 35 kW/m^2, as was done in the CBUF project. Time-dependent flame areas were estimated using infrared images taken during the full-scale tests. A computer code was developed to implement Equation (1), and the model was used to predict the heat release rates measured during the furniture calorimeter tests of the foam. The CBUF model was able to successfully predict the initial growth phase of the fires and predictions of peak heat release rates were within 17% of measured values. In general, the CBUF model did a better job of predicting heat release rates in edge ignition tests (e.g., Figure 3) than in centre ignition tests (e.g., Figure 4). The model had less success in predicting heat release rates later in the growth phase and during the decay phase of the fires, and did not appear to capture all of the physics of the full-scale tests, in particular foam melting and subsequent liquid pool burning.

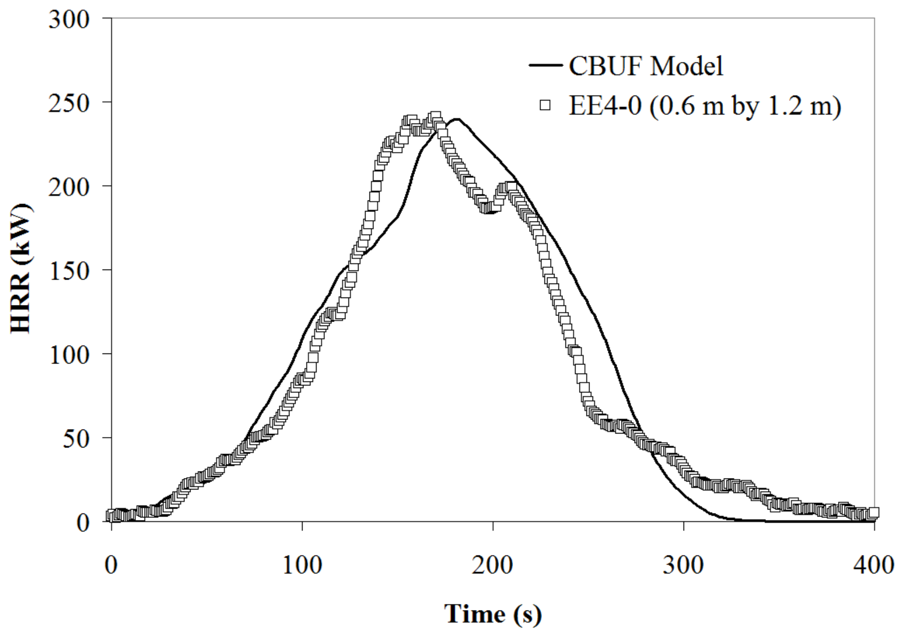


Figure 3. Comparison of Heat Release Rates Predicted Using CBUF Model and Measured During Furniture Calorimeter Test of 0.6 m by 1.2 m by 10 cm Thick Piece of Polyurethane Foam Ignited on One Edge [14].

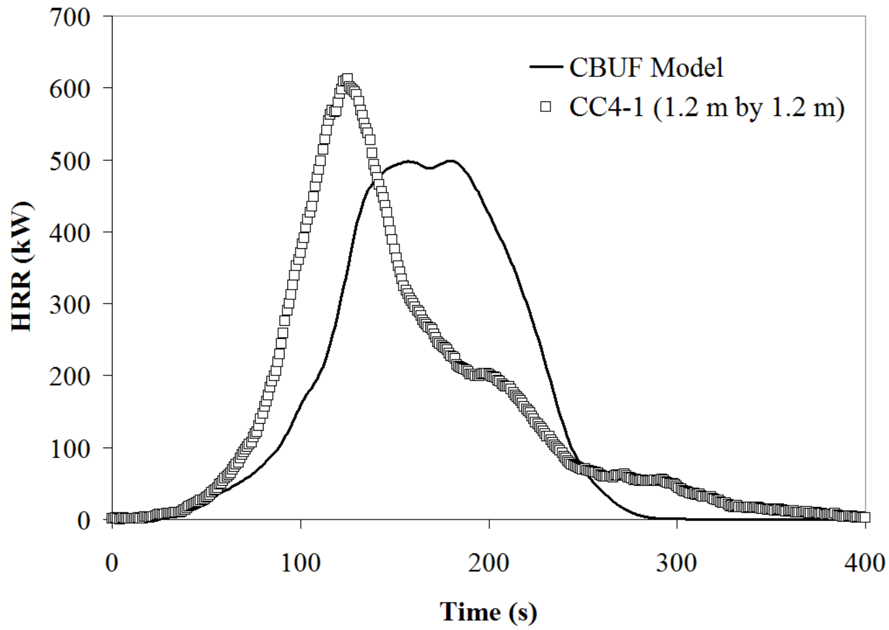


Figure 4. Comparison of Heat Release Rates Predicted Using CBUF Model and Measured During Furniture Calorimeter Test of 1.2 m by 1.2 m by 10 cm Thick Piece of Polyurethane Foam Ignited in the Centre [14].

Two issues were identified as a result of this second study. The first issue related to whether the 35 kW/m^2 incident heat flux used in the cone calorimeter tests to generate heat release rate density data for use in the model was optimal for this purpose. The selection of an appropriate incident heat flux is also an issue of broader concern in the development of test standards [18]. While many cone calorimeter test standards (e.g., ASTM E 1474 [10]) specify an incident heat flux of 35 kW/m^2, other standards use lower or higher incident heat fluxes. The choice of incident heat flux will influence the time to ignition and the burning behaviour of the specimen. This is important from a regulatory perspective, as well as when using cone calorimeter data in models to predict heat release rates in full-scale fire tests. Therefore, in the present work, the influence of the incident heat flux setting on measured heat release rates was investigated by conducting cone calorimeter tests of polyurethane foams at incident heat fluxes of 25, 35, 50 and 75 kW/m^2. The resultant heat release rate density data was then applied with the CBUF model to determine the effect of incident heat flux on predicted full-scale fire test results.

The second issue that was identified related to the ability of the CBUF model to predict full-scale fire test results for differing thicknesses of foam. As noted earlier, the CBUF model used here was based on a model that was originally developed for relatively thin room lining materials. The results of the second UofS/UW study demonstrated that heat transfer through the thickness of the 10 cm thick foam may not be adequately simulated by the CBUF model, as the combustion behaviour and thus burning rates through the thickness of the foam were different in the cone versus the furniture calorimeter tests. Therefore, in the present study, foam specimens ranging in thickness from 2.5 to 10 cm were tested in both the cone and furniture calorimeter.

This paper first describes the computer code that was developed to implement the CBUF model, and briefly discusses the results of the cone and furniture calorimeter tests that were conducted. Predicted heat release rates are then compared with measurements made in the furniture calorimeter. The effect of the incident heat flux used to generate the cone calorimeter data is discussed, along with the ability of the CBUF model to predict heat release rates for different thicknesses of foam. Future work to further improve the model is also discussed.

2. FIRE MODEL

The convolution integral model in Equation (1) was implemented using Microsoft Excel®. Excel was well suited for the development of this code due to the small sizes of the data files that were to be processed, and the relative simplicity of the numerical techniques that were implemented in this research. The specific technique that was employed to perform the convolution process is known as discrete convolution and for this specific application it takes the form of

$$Q^N = \sum_{i=1}^{N} \Delta A_f^i \, q''^{N-1} \qquad (2)$$

where: Q^N is the predicted full scale heat release at increment N (kW),

ΔA_f^i is the differential burning area at increment i (m^2), and

q''^{N-1} is the heat release rate density at time increment N-1 (m^2).

The computer model was validated using an exact solution of Equation (1) based on simple expressions for q"(t) and $A_f(t)$. It was also determined that 1 s, the rate at which data was sampled in the cone and furniture calorimeter tests, was an appropriate time step when modelling the full-scale tests considered here. Expressions for q"(t) and $A_f(t)$ used in the spreadsheet were determined using data from cone calorimeter and furniture calorimeter tests of polyurethane foam, which are described in the next sections. More details on the numerical model can be found in [19].

One of the challenges involved in evaluating the CBUF model is that it requires two sets of time-dependent input, heat release rate density and flame area. In practice, heat release rate density would be measured in cone calorimeter tests, while a flame spread model would be used to generate time-dependent flame areas. In this work, as in the second UofS/UW study, it was decided to evaluate the CBUF model by using the actual flame areas measured in the same tests in which the full-scale heat release rates were measured. This allowed the heat release rate density portion of the model to be isolated, an important consideration given that one of the objectives of this study was to explore the influence of the incident heat flux used in the cone calorimeter tests. The ultimate goal is to develop a method which would not require execution of any full-scale tests. Therefore, if the CBUF model shows promise, a stand-alone flame spread model could be developed and validated using full-scale test data. This flame spread model could also be used in conjunction with other models to predict temperatures at detectors and other locations in a room, which would be useful in many facets of design.

3. EXPERIMENTAL

3.1 Materials

Polyurethane foam samples were obtained from several branches of a Canadian retail chain in Kitchener-Waterloo and Saskatoon between July, 2006 and September, 2010. These foams are considerably less dense than foams typically found in solid-core mattresses, as they are mainly intended to be used as camping pads. However, these foams could be easily obtained at retail locations across Canada, and could be quickly and consistently ignited using a small ignition source, resulting in self-propagating fires that consumed practically the entire specimen. No detailed information was available on the base chemical composition of the foam; however, based on their ignition and burning characteristics, they did not appear to contain a fire retardant. Nonetheless, such knowledge was not deemed important to the present study as it was the intent here to develop a somewhat general flame spread predictive tool which preferably would not require in-depth knowledge of fuel formulation and detailed combustion chemistry.

In previous research, cone and furniture calorimeter specimens were prepared from rolls of foam with nominal dimensions of 1.2 m by 1.8 m by 10 cm thick [14]. In order to examine the ability of the CBUF model to predict heat release rates in full-scale tests of thinner foams, foams that were sold in rolls with nominal dimensions of 0.5 m by 1.4 m by 2.5 cm thick, 0.6 m by 1.8 m by 5.0 cm thick and 0.6 m by 1.8 m by 7.5 cm thick were also purchased. The experimental data reported in this paper includes both the data previously reported for the 10 cm thick foams [14], as well as the data obtained during the cone and furniture calorimeter tests of the thinner foams.

3.2 Cone Calorimeter Testing

Cone calorimeter specimens, 10 cm by 10 cm, were prepared from each of the four thicknesses of foam (Table 1). All specimens were tested in the cone calorimeter laboratory at the University of Saskatchewan, where ambient temperature was controlled by the building air handling system and varied between 21.0 and 23.9°C over the time during which the small-scale tests were conducted. The building system does not control relative humidity; however, humidity only varied from 22 to 24% RH during the test period. Prior to testing, specimens were placed in a sample conditioner for at least 24 hours, where they were conditioned at 22°C ± 5°C and 50% ± 5% RH using an aqueous solution of magnesium chloride with a density of 1.27 g/cm^3.

Table 1. Mass and thickness information for cone calorimeter test series

Test Series	Mass (g) Ave.	Mass (g) (σ)	Thickness (cm) Ave.	Thickness (cm) (σ)
1-25	4.22	(0.03)	2.5	(0.00)
1-35	4.18	(0.05)	2.5	(0.06)
1-50	4.22	(0.03)	2.5	(0.06)
1-75	4.23	(0.16)	2.5	(0.00)
2-25	8.09	(0.08)	5.0	(0.06)
2-35	8.28	(0.06)	5.0	(0.06)
2-50	8.20	(0.06)	5.0	(0.00)
2-75	8.11	(0.14)	5.0	(0.00)
3-25	12.81	(0.26)	7.3	(0.00)
3-35	12.59	(0.13)	7.4	(0.06)
3-50	12.61	(0.37)	7.4	(0.06)
3-75	12.71	(0.19)	7.3	(0.06)
4-25	15.88	(0.14)	9.8	(0.15)
4-35	15.96	(0.15)	9.8	(0.00
4-50	15.90	(0.09)	9.7	(0.06)
4-75	15.95	(0.05)	9.8	(0.00)

The specimens were partially wrapped in aluminum foil, as shown in Figure 5, to prevent the spill of molten materials during tests. Specimens were then placed on top of a small piece of cement board wrapped in aluminum foil, which had been placed on top of the load cell in the cone calorimeter (Fire Testing Technology, East Grinstead, UK). For each foam thickness, three tests were conducted at each of four different incident heat fluxes: 25, 35, 50 and 75 kW/m^2. Results of the three tests were averaged to generate the data for each level of incident heat flux. Cone calorimeter tests reported in this paper are labeled using the following convention: foam thickness (in.)-heat flux (kW/m^2)-test number (e.g., 1-35-1 is the first in the series of tests of 2.5 cm (1 in.) thick pieces of foam conducted using an incident heat flux of 35 kW/m^2). Gas concentrations and other measurements were recorded at 1 s intervals and used to calculate the heat release rate density using oxygen consumption calorimetry principles. The incident heat flux was set using a Schmidt-Boelter gauge (Medtherm, Huntsville, AL) that was positioned 2.5 cm below the cone heater, at the same height as the top of the foam specimen. Average values of the heat release rate density measured at each time step in the three tests were used in the CBUF model.

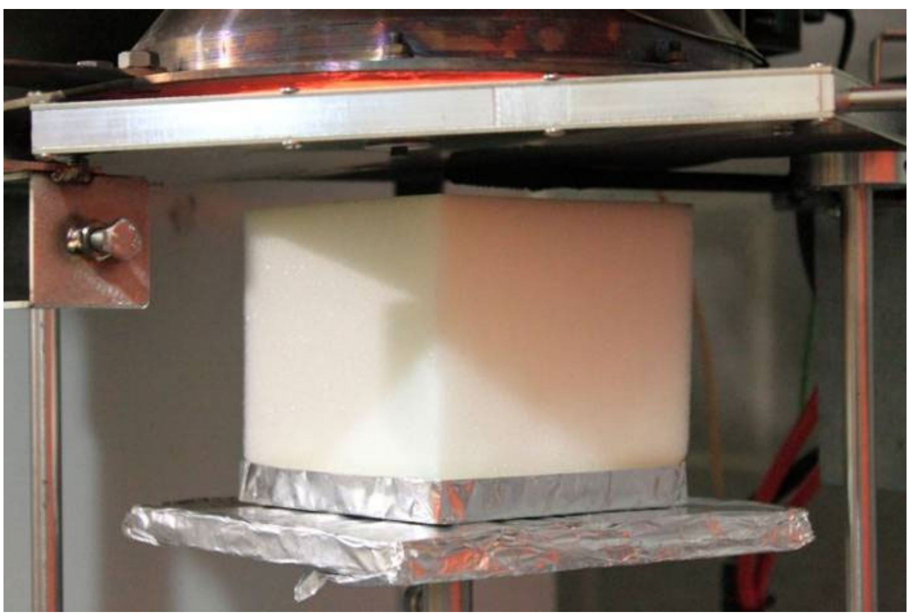


Figure 5. Cone Calorimeter Tests of Polyurethane Foam Specimens.

3.3 Furniture Calorimeter Testing

Dimensions of individual furniture calorimeter specimens are given in Tables 2 and 3, along with the dates of testing and conditions in the laboratory at the time of testing. Furniture calorimeter tests reported in this paper are labeled using the following convention: ignition location-foam thickness (in.)-test number (e.g., C3-2 is the second in the series of tests of 7.5 cm (3 in.) thick foam that were ignited in the centre). For the 10 cm thick foam, two widths of specimens were tested. The tests of 0.6 m wide specimens are labeled using a single C or E, while the tests of the 1.2 m wide specimens are labeled using CC and EE.

The average density of the test specimens was 17.0 kg/m^3, and the density of individual specimens ranged between 15.9 and 19.3 kg/m^3, with a standard deviation of 1.4 kg/m^3. The main reason for the variation in the density values was the degree to which the foam expanded after it was unwrapped and unrolled. As the rolls of foams were purchased over a relatively long period of time, it is also expected that the composition of individual foam specimens may not be exactly the same due to changes in manufacturing of the product, and possible foam aging effects.

Furniture calorimeter testing was conducted in the main burn hall at the University of Waterloo Live Fire Research Facility during May, 2008, June, 2009 and July, 2010. Specimens were conditioned for at least 24 hours in the cone calorimeter laboratory and other rooms within the facility prior to testing. Temperatures and relative humidity in the rooms used for conditioning during the test period were between 22 and 23°C, and 32 and 67% respectively. Conditions in these rooms were loosely controlled using an air handling system. A dehumidifier was also run during the day, if necessary. However, this dehumidifier was not run during evenings or the weekend.

The temperature and relative humidity in the main burn hall of the facility were not controlled, as the facility has large open fan dampers and a large door which is often open to the outside. Therefore, as shown in Tables 2 and 3, there were significant variations in the environmental conditions during some of the tests. The humidity ratio of the air in the laboratory ranged between a low of 0.004 kg of water vapour per kg dry air for some of the tests in May, 2008 and a high of 0.015 kg of water vapour per kg dry air during some of the tests in July, 2010.

Table 2. Furniture Calorimeter Test Specimens and Test Dates/Environmental Conditions (Centre Ignition Location)

Test Specimen	Test Date (temperature & relative humidity)	Dimensions (cm)			Mass (kg)
		Width	Length	Thickness	
C1-1	July 19, 2010 (26°C, 56%)	61	52	2.5	0.13
C1-2	July 20, 2010 (25°C, 56%)	61	53	2.5	0.13
C1-3	July 20, 2010 (29°C, 43%)	61	53	2.5	0.14
C1-4	July 21, 2010 (27°C, 60%)	61	52	2.5	0.14
C2-1	July 19, 2010 (26°C, 54%)	61	63	5.0	0.31
C2-2	July 20, 2010 (28°C, 43%)	61	62	5.0	0.32
C2-3	July 21, 2010 (27°C, 59%)	61	63	5.0	0.31
C3-1	July 20, 2010 (24°C, 66%)	62	61	7.5	0.50
C3-2	July 20, 2010 (29°C, 40%)	61	62	7.5	0.47
C3-3	July 21, 2010 (28°C, 56%)	62	61	7.5	0.47
C4-1	May 15, 2008 (17°C, 38%)	60	62	9.3	0.58
C4-2	May 15, 2008 (18°C, 36%)	60	62	9.5	0.58
C4-3	July 21, 2010 (28°C, 53%)	59	61	9.3	0.58
CC4-1	May 16, 2008 (18°C, 36%)	121	124	9.7	2.31
CC4-2	July 22, 2010 (25°C, 59%)	122	124	9.8	2.53
CC4-3	July 21, 2010 (28°C, 50%)	125	122	9.3	2.35

Table 3. Furniture Calorimeter Test Specimens and Test Dates/Environmental Conditions (Edge Ignition Location)

Test Specimen	Test Date (temperature & relative humidity)	Dimensions (cm)			Mass (kg)
		Width	Length	Thickness	
E1-1	June 18, 2009 (16°C, 90%)	51	142	2.5	0.35
E1-2	June 18, 2009 (16°C, 90%)	52	142	2.5	0.30
E1-3	June 18, 2009 (16°C, 90%)	52	142	2.5	0.30
E2-1	July 20, 2010 (26°C, 49%)	63	120	5.0	0.63
E2-2	July 21, 2010 (24°C, 82%)	62	122	5.0	0.63
E2-3	July 21, 2010 (28°C, 53%)	63	119	5.0	0.61
E3-1	July 20, 2010 (28°C, 44%)	62	123	7.5	1.04
E3-2	July 21, 2010 (25°C, 75%)	62	124	7.5	0.95
E3-3	July 21, 2010 (27°C, 53%)	62	124	7.5	0.96
E4-0	May 14, 2008 (14°C, 72%)	61	126	10.0	1.23
E4-1	May 15, 2008 (16°C, 41%)	61	126	9.3	1.38
E4-2	July 21, 2010 (26°C, 68%)	61	125	9.3	1.19
E4-3	July 22, 2010 (23°C, 69%)	61	125	9.3	1.17
EE4-1	May 15, 2008 (18°C, 35%)	125	122	8.8	2.76
EE4-2	May 16, 2008 (14°C, 45%)	125	122	9.8	2.43
EE4-3	July 22, 2010 (27°C, 54%)	122	122	9.8	2.32

Specimens were placed on top of an electronic load cell that was covered with a ceramic protective sheet, cement board and aluminum foil sheets (Figure 6)**.** The entire assembly was levelled and placed on fire bricks under the furniture calorimeter hood. The test specimens were ignited using either a small hand-held propane torch (May, 2008 tests) or a butane barbecue lighter (June, 2009 and July, 2010 tests, Figure 7). It was estimated via cone calorimeter testing that the heat release rate of the former ignition source is 1.3 kW and the latter is 0.1 kW. Once the specimen was ignited, testing followed standard test procedures for large-scale oxygen consumption calorimetry.

Two ignition locations were used for testing. For centre ignition tests, a 6.4 cm diameter hole with a depth of 1.3 cm was cut at the centre of the specimen to ensure a consistent ignition location for each test (Figure 7a). The ignition source was positioned at this location. For edge ignition, the ignition source was placed on a mark on the top surface of the specimen at the midpoint point along the width (Figure 7b).

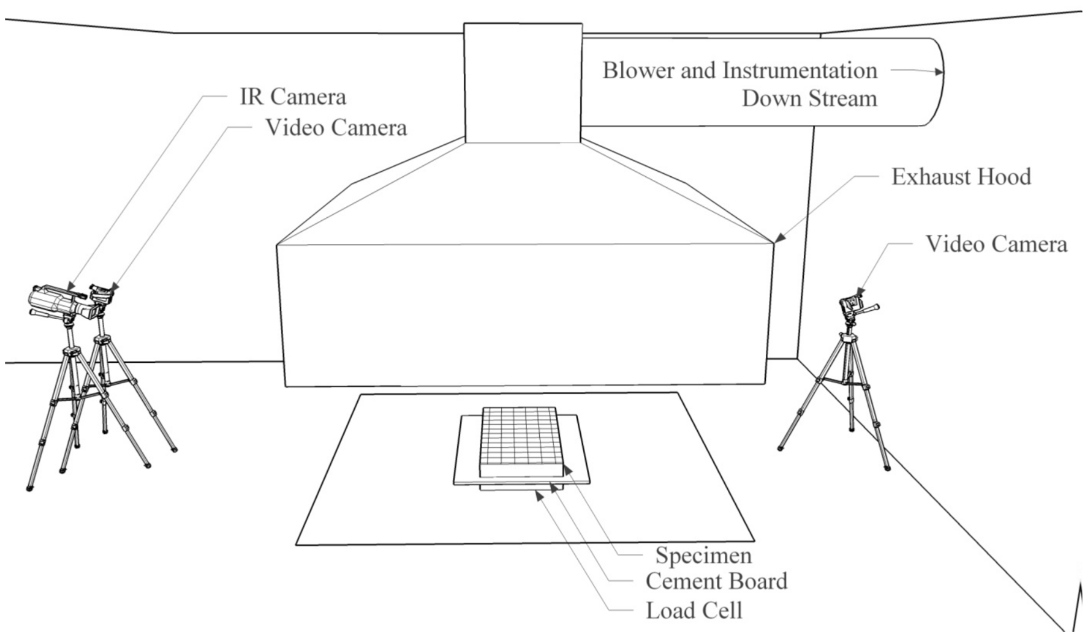
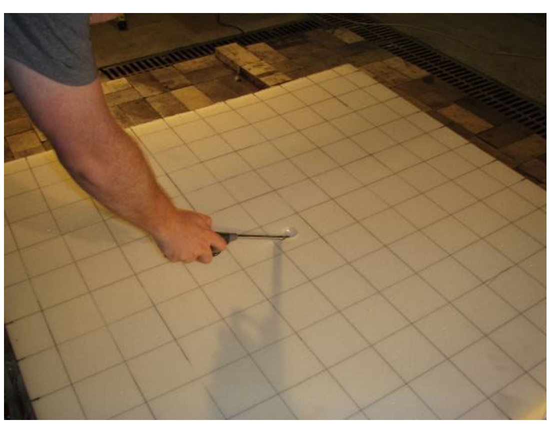
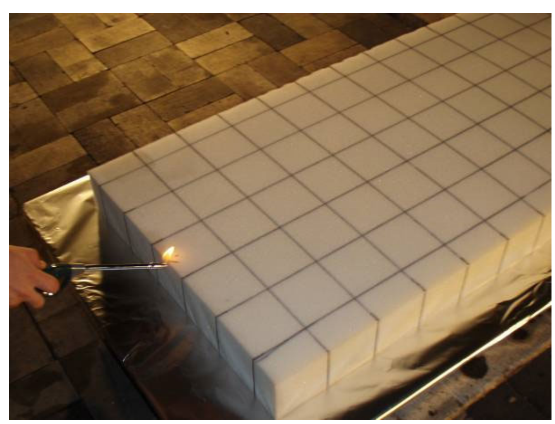


Figure 6. Furniture Calorimeter Test Set Up, Including Positions of Infrared (IR) and Video Cameras.



(a) Centre Ignition



(b) Edge Ignition

Figure 7. Ignition Locations on Polyurethane Foam Specimens.

A FLIR ThermaCAM® S60 infrared (IR) camera (FLIR Systems, Burlington, ON) with a spectral range of 7.5 to 13 µm, and one or two Sony MiniDV camcorders (Sony of Canada, Toronto, ON) were used to record each of the fire tests. Still photographs were also taken at various times during the test using an Olympus Stylus 770SW (Olympus Canada Inc., Markham, ON) or a Panasonic DMC-LZ10 (Panasonic, Canada, Inc., Mississauga, ON) digital camera. Examples of photographs taken during centre and edge ignition tests are shown in Figures 8 and 9, respectively. The time-dependent flame area ($A_f(t)$) for use in Equations (1) and (2) was determined by analyzing footage from the IR camera using an in-house computer code that was written using MATLAB® (Mathworks, Inc., Natick, MA) [19]. Since this flame spread rate measurement procedure was largely automated, results were verified by comparing the flame areas determined using the computer code with those determined by counting the number of 10 cm by 10 cm squares that were ignited at 30 s intervals for a sample of the tests. It was found that flame areas determined using the two different methods were within 150 cm^2 of each other.

(a) 1 min.

(b) 1 min. 40 s

(c) 2 min.

(d) 3 min.

Figure 8. Photographs Taken During Test CC4-3 and Approximate Time After Ignition.

(a) 1 min. 40 s

(b) 2 min. 15 s

(c) 3 min.

(d) 4 min.

Figure 9. Photographs Taken During Test E2-2 and Approximate Times After Ignition.

4. RESULTS AND DISCUSSION

4.1 Cone Calorimeter Tests

Figures 10 and 11 are plots of the heat release rate density for three individual tests conducted in each of the 1-25 and 4-50 test series, respectively. Two distinct stages of the combustion process were observed for all thicknesses of foam burned in the cone calorimeter. The first stage of combustion took place while the structure of the foam was collapsing, while the second stage took place while the foam was in a liquid state. These two stages correspond to the two distinct peaks in the cone calorimeter heat release density curves in Figures 10 and 11. The general shape of the heat release rate curve was similar in each of the individual tests within a series, with more consistency in the earlier portions of the tests and the first peak of the individual curves than in the second peak and the decay periods of the individual curves.

Table 4 summarizes the heat release rate measurements for the four thicknesses of foam that were tested. It should be noted that average heat release densities in this Table were calculated using the entire duration of time that the specimen was burning (i.e., from the start of the test until "flame out" was observed). Table 4 demonstrates that there was a good level of consistency in measured values of peak and average heat release rate within each test series, and a very good level of consistency in the values of total heat release, especially when total heat release is normalized using the mass of the specimen. Further, measured values of THR/mass are in good agreement with values of heat of combustion reported in the literature for polyurethane foams (e.g., 24.4 MJ/kg in [12]).

Heat release rate density curves measured using each of the four different incident heat fluxes are shown for each thickness of foam in Figures 12-15. In general, all of the heat release rate density curves exhibited the two distinct peaks discussed above. The one exception was the test series in which the 2.5 cm thick foam was tested using an incident heat flux of 75 kW/m^2 (Figure 12). In this case, due to the high incident heat flux the foam heated and decomposed very quickly making it difficult to differentiate between the first and second peak in the heat release rate density curve for this sample.

For a particular thickness of foam, an increase in incident heat flux tended to increase the magnitude of each of the two peaks (and therefore the peak heat release rate density value in

Table 4), with the associated reduction in the total time of burning for that thickness of foam. For a particular level of incident heat flux, however, the duration of the burning period increased by approximately 30-40 s for each 2.5 cm increase in foam thickness (Figures 12-15).

For a particular thickness of foam, average heat release rate densities measured during the burning of the foam were similar for the tests conducted at 25 and 35 kW/m^2, and then increased with incident heat flux. At the higher levels of incident heat flux, the heat release rate density appears to increase as the foam thickness increases from 2.5 to 5.0 cm and then levels and decreases for thicker foam specimens (7.5 to 10.0 cm thick). This may be a result of the variation in incident heat flux which occurs during testing due to the steadily increasing distance between the cone calorimeter element and the receding surface of the sample as the foam melts and burns. This decrease in incident heat flux to the surface of the foam will be discussed in more detail later in the paper.

Table 4. Summary of Heat Release Rate Measurements From Cone Calorimeter Tests Using Different Incident Heat Fluxes

Nominal Thickness (cm)	Incident Heat Flux (kW/m^2)	Peak HRR Density (kW/m^2)		Ave. HRR Density (kW/m^2)		THR (MJ/m^2)		THR/mass (MJ/kg)	
		Ave.	(σ)	Ave.	(σ)	Ave.	(σ)	Ave.	(σ)
2.5	25	428	(34.4)	241	(7.2)	10.5	(0.19)	24.8	(0.59)
	35	556	(29.6)	225	(11.8)	10.4	(0.07)	24.8	(0.09)
	50	749	(63.5)	322	(72.8)	11.1	(0.28)	26.2	(0.56)
	75	950	(57.4)	370	(25.6)	11.3	(0.39)	26.7	(0.88)
5	25	419	(13.8)	245	(12.5)	19.6	(0.31)	24.3	(0.35)
	35	472	(19.5)	251	(2.1)	19.5	(0.09)	23.6	(0.26)
	50	670	(17.9)	382	(14.6)	19.7	(0.40)	24.0	(0.45)
	75	989	(26.6)	505	(13.3)	21.0	(0.24)	25.9	(0.09)
7.5	25	424	(21.4)	260	(10.2)	31.3	(0.55)	24.4	(0.13)
	35	504	(20.6)	274	(14.1)	30.5	(1.09)	24.2	(0.66)
	50	603	(9.9)	367	(13.9)	30.6	(1.22)	24.2	(0.51)
	75	919	(16.4)	520	(4.8)	31.5	(0.03)	24.8	(0.28)
10	25	373	(4.8)	246	(7.9)	38.9	(0.37)	24.5	(0.41)
	35	420	(19.5)	273	(21.6)	38.0	(0.63)	23.8	(0.52)
	50	503	(52.8)	347	(14.9)	37.6	(0.88)	23.7	(0.53)
	75	723	(33.0)	449	(50.5)	39.6	(0.18)	24.9	(0.17)

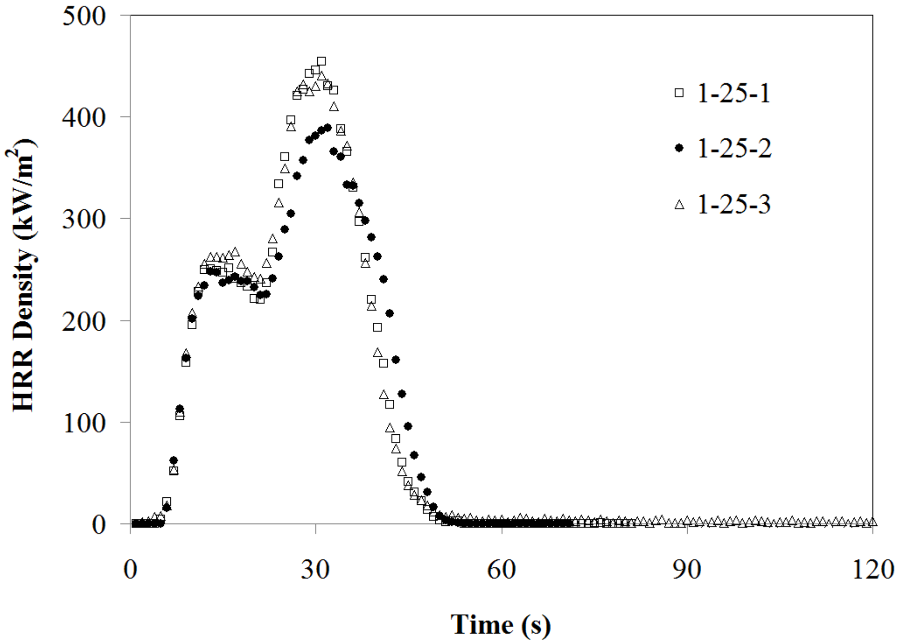


Figure 10. Heat Release Rate Density Measurements in Cone Calorimeter Tests of 2.5 cm Thick Foam Specimens Exposed to Incident Heat Flux of 25 kW/m^2.

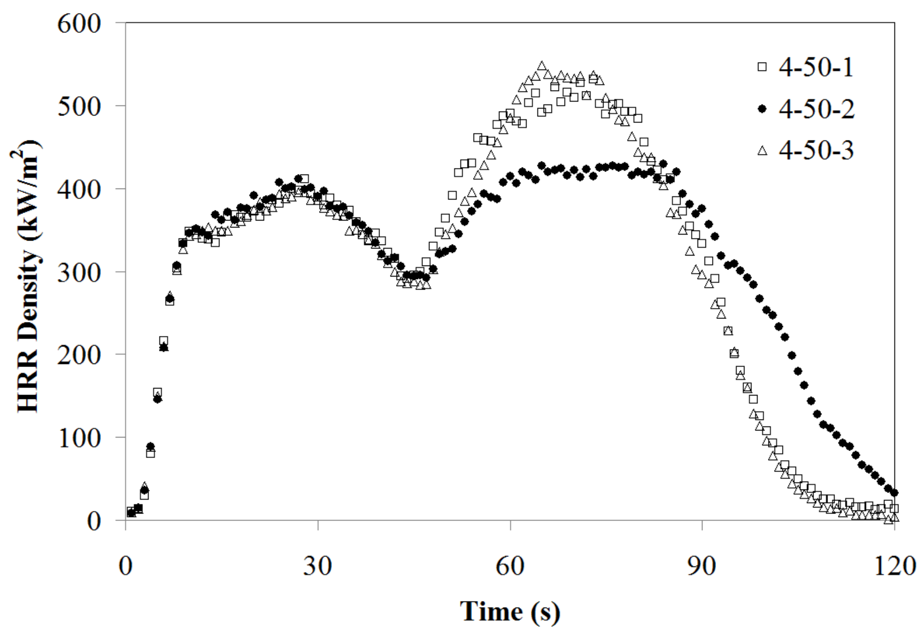


Figure 11. Heat Release Rate Density Measurements in Cone Calorimeter Tests of 10 cm Thick Foam Specimens Exposed to Incident Heat Flux of 50 kW/m^2.

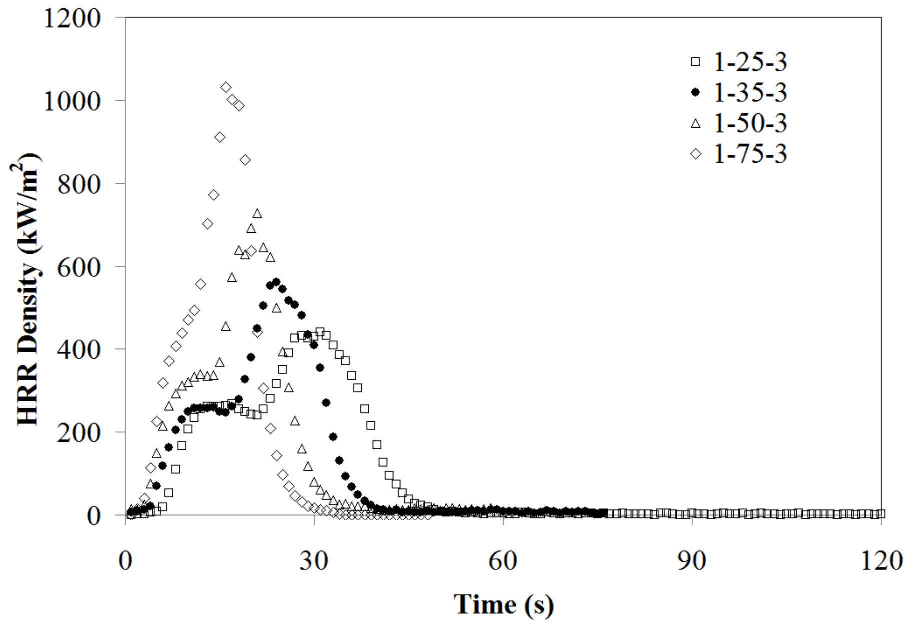


Figure 12. Heat Release Rate Density Measurements During Cone Calorimeter Tests of 2.5 cm Thick Foam Specimens Exposed to Incident Heat Fluxes of 25, 35, 50 and 75 kW/m^2.

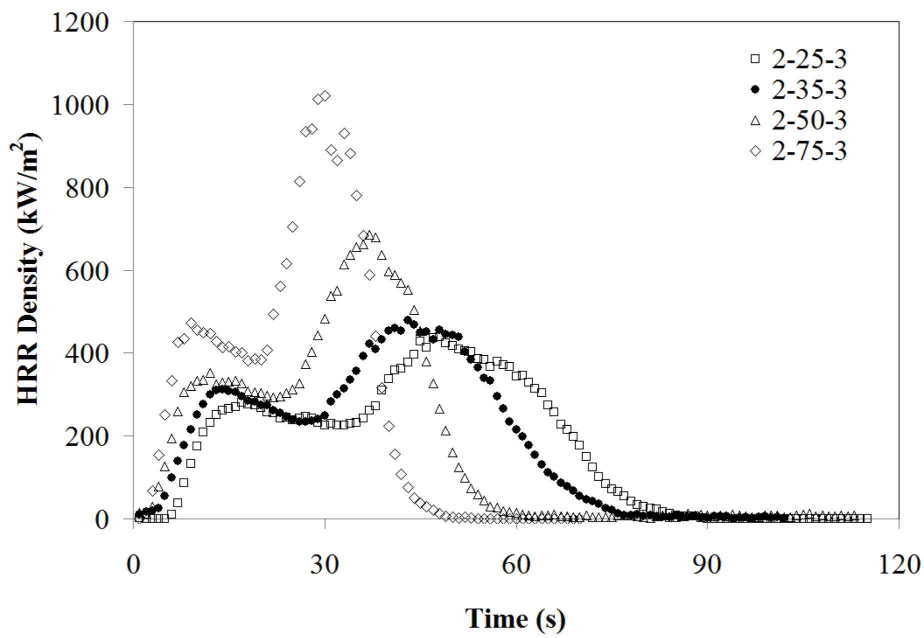


Figure 13. Heat Release Rate Density Measurements During Cone Calorimeter Tests of 5 cm Thick Foam Specimens Exposed to Incident Heat Fluxes of 25, 35, 50 and 75 kW/m^2.

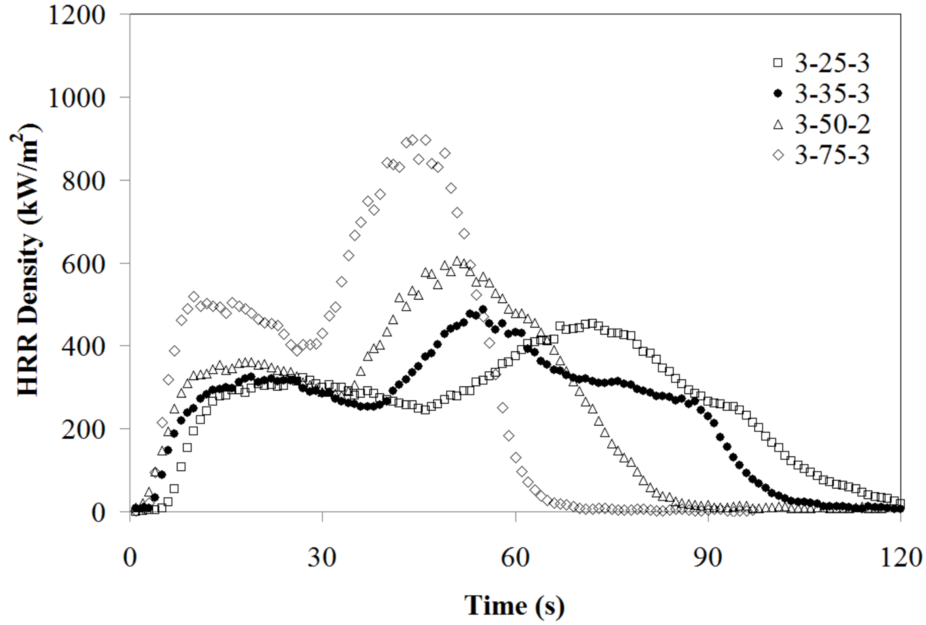


Figure 14. Heat Release Rate Density Measurements During Cone Calorimeter Tests of 7.5 cm Thick Foam Specimens Exposed to Incident Heat Fluxes of 25, 35, 50 and 75 kW/m^2.

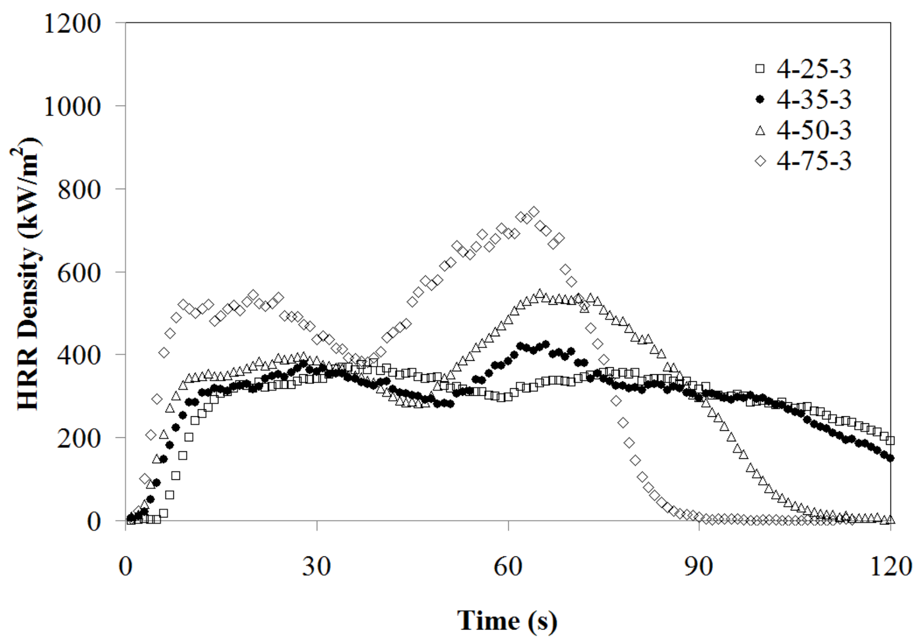


Figure 15. Heat Release Rate Density Measurements During Cone Calorimeter Tests of 10 cm Thick Foam Specimens Exposed to Incident Heat Fluxes of 25, 35, 50 and 75 kW/m^2.

4.2 Furniture Calorimeter Results

Examples of the variations between heat release rates measured in individual tests within each test series are shown in Figures 16 (centre ignition) and 17 (edge ignition). There was a good level of repeatability in the test results. The growth portions of the curves for all of the individual tests within a test series (i.e., tests with foams of the same size and ignition location) were very similar. Most peak heat release rates for individual tests were within ±10% of the average for that particular test series. Practically all total heat release values for individual tests were within ±8% of the average for that particular test series. Since the mass of individual specimens varied within a test series, total heat release per unit mass values were also calculated. All of these latter values for individual tests were within 8% of the average for that particular test series, with an overall average THR/mass of 23.1 MJ/kg. This value is slightly lower than, but still within 8% of, the average THR/mass of 24.7 MJ/kg measured in the cone calorimeter tests above. Small differences between results of tests of individual foam specimens may have been due to differences in environmental conditions during testing, foam aging and/or changes in the exact composition of the foam over the time period that the samples were purchased. Despite these factors, there was a very good level of repeatability amongst test results in both the cone and furniture calorimeters.

Area burning rates measured using the IR video are shown in Figure 18 for centre ignition tests of the 0.6 m by 0.6 m foams of various thickness. Area burning rates for edge ignition tests of the 0.6 m by 1.2 m foams of various thickness are shown in Figure 19. In general for foams ignited in the same location, flame area increased more quickly as the foam thickness increased (Figures 18 and 19). This observation can be explained in terms of the effects of the slab thickness on heat transfer into and through the foam combined with local variations in heat flux to each portion of the larger foam sample as the flames develop and grow. For thin slabs, the flames spread across the surface but also through the thickness of the sample so that when the maximum flame area was reached the full thickness of the foam had already been consumed as evidenced in Figure 9(c,d) for even the 5.0 cm thick slab. As the slab thickness increased, and most markedly for the case of centre ignition, the flame spread across the surface of the sample more quickly than through the sample thickness and a pool of melted foam formed on top of the bottom solid portions of the slab (Figure 8c), even until the time when maximum flame areas were reached. This resulted in larger flame areas and higher incident heat flux to the unburned foam than in the comparable cases with thinner slabs, as supported by the higher temperatures observed ahead of the flames in the infrared images as well.

Area burning rates for the centre and edge ignition tests of the 1.2 m by 1.2 m by 10 cm thick foam are shown in Figure 20. For 1.2 m by 1.2 m by 10 cm thick foam specimens, flame area increased at a similar rate for the first 80-90 s regardless of ignition location, and then increased at a significantly quicker rate for the foams that were ignited in the centre (Figure 20). This is a result of differences in melting and pooling for edge versus center ignition as noted above, as well as the fact that for edge ignition, the flame spreads from the ignition location out first to the two sides of the slab and then the front progresses to the far end of the slab, while for centre ignition, the flame spreads in all directions simultaneously.

It should be noted that the technique used in this study only considered flame spread on the upper surface of the specimen, but did not account for any flame spread that might have occurred along the outside edges of the specimens. For the thicker specimens, this additional area can be very significant relative to the flaming area of the top of the specimen. For example, the area represented by the four 10 cm thick sides of the E4 foam is 50% of the area of the top surface of the foam (0.6 m by 1.2 m). As will be discussed later in the paper, the technique used also did not reduce the flame area at a particular time to correct for portions of the foam that had already completely burned.

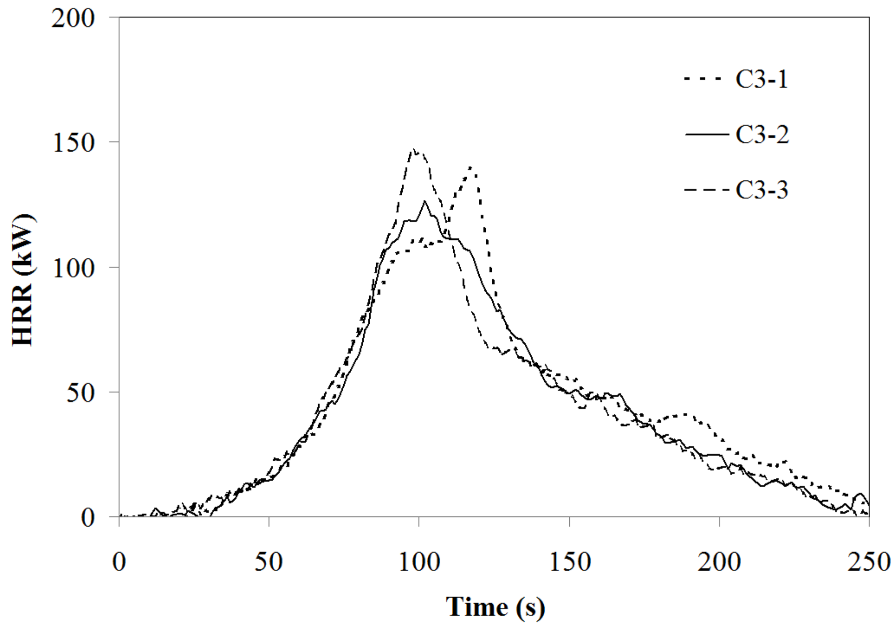


Figure 16. Heat Release Rates Measured During Individual Tests in Test Series C3 (0.6 m by 0.6 m by 7.5 cm Thick, Centre Ignition).

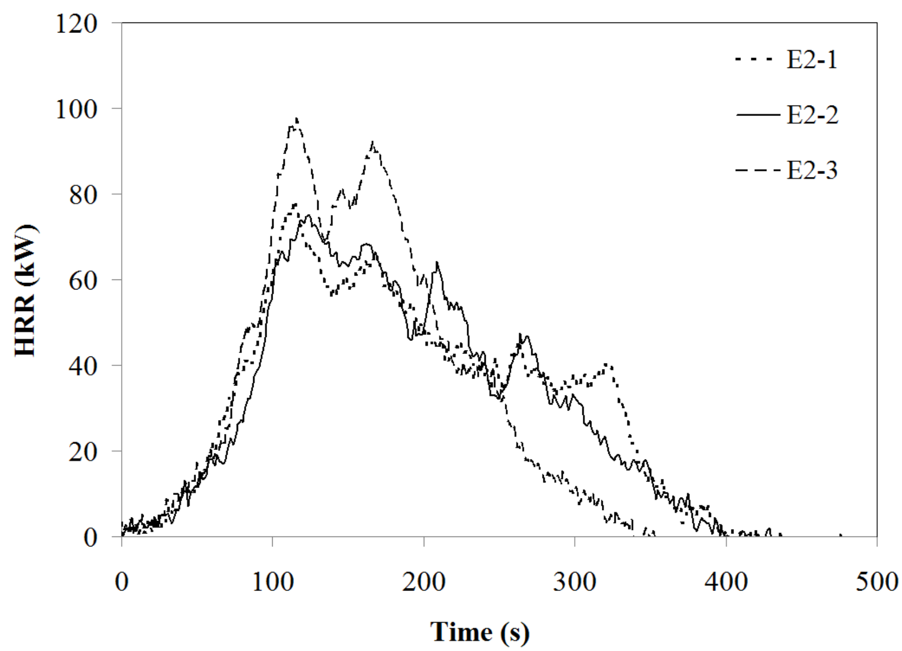


Figure 17. Heat Release Rates Measured During Individual Tests in Test Series E2 (0.6 m by 1.2 m by 5.0 cm Thick, Edge Ignition).

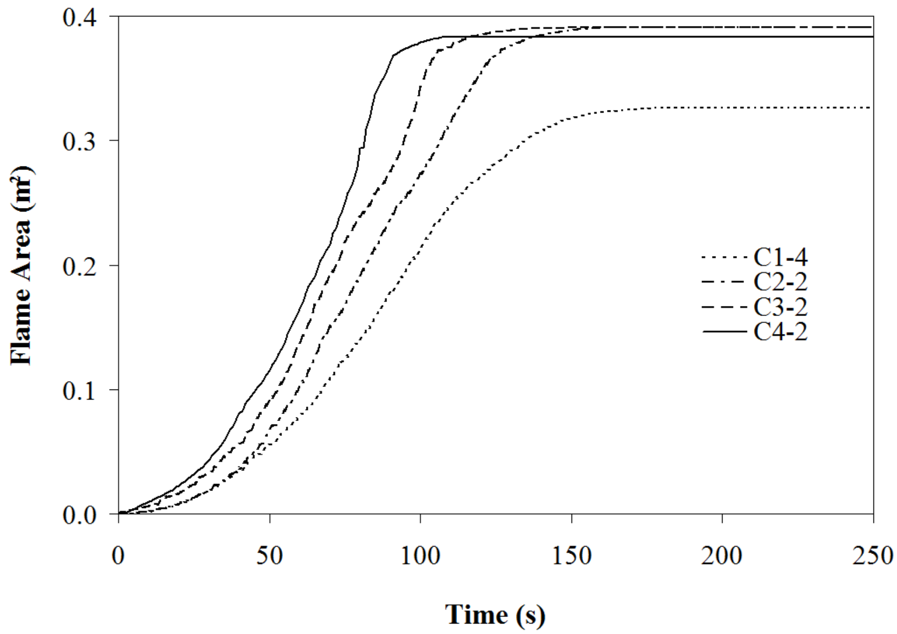


Figure 18. Flame Areas Measured Using IR Video Records of Tests of Polyurethane Foam Specimens Ignited at the Centre (0.6 m by 0.6 m, Thicknesses of 2.5 cm (C1-4), 5 cm (C2-2), 7.5 cm (C3-2), 10 cm (C4-2)).

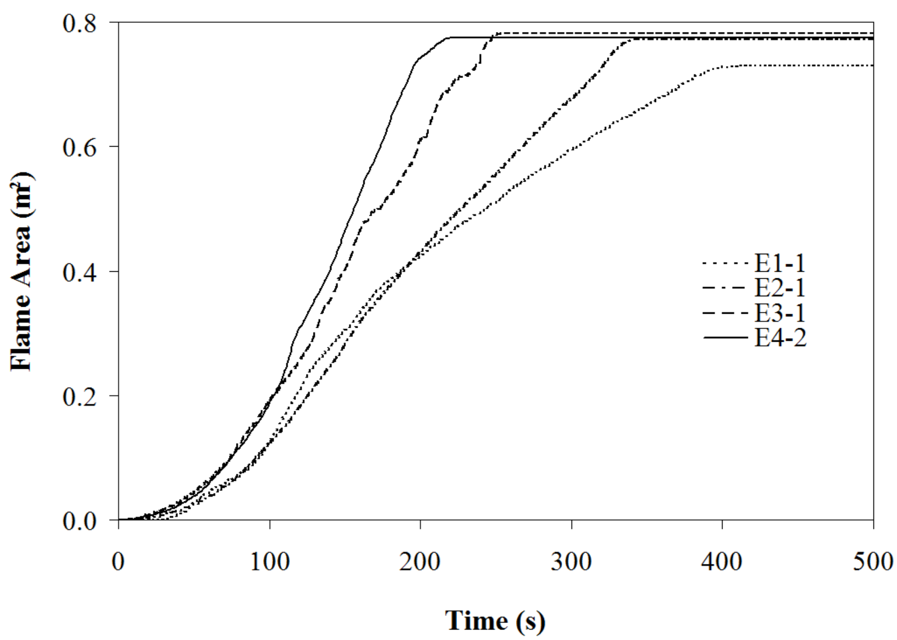


Figure 19. Flame Areas Measured Using IR Video Records of Tests of Polyurethane Foam Specimens Ignited at the Edge (0.6 m by 1.2 m, Thicknesses of 2.5 cm (E1-1), 5 cm (E2-1), 7.5 cm (E3-1), 10 cm (E4-1)).

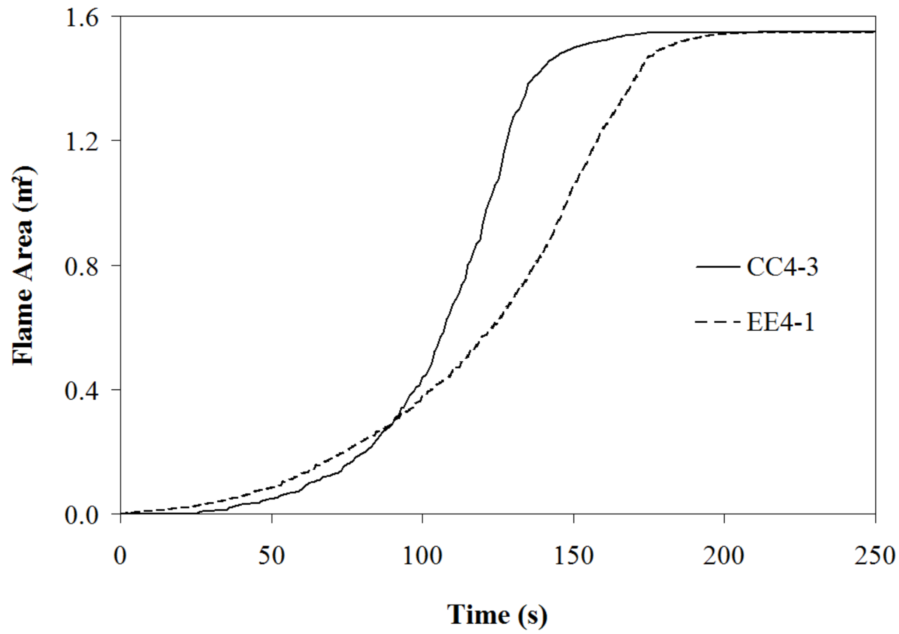


Figure 20. Flame Areas Measured Using IR Video Records of Tests of Polyurethane Foam Specimens (1.2 m by 1.2 m by 10 cm Thick, Centre Ignition (CC4-3), Edge Ignition (EE4-1)).

4.3 Comparison of Predicted and Measured Heat Release Rates

Average heat release rate density versus time curves were generated, based on the results of the three cone calorimeter tests conducted for each thickness of foam at a single incident heat flux (e.g., the average heat release rate density curve for test series 1-25). These average heat release rate density curves were used in Equation (2) for predicting all of the test results for a particular full-scale test series (e.g., test series C4). The area burning rate (A_f) corresponding to a particular full-scale test was also used in Equation (2) (e.g., test C4-1). In Figures 21 through 30, heat release rates predicted by the CBUF model are compared with heat release rates measured in individual tests from each of the test series. Tables 5 and 6 compare average values of peak heat release rate, time to peak heat release rate and total heat release predicted using the data gathered at each of the four incident heat fluxes with the average values measured during each test series. Figures 31 and 32 compare the average predicted and measured values of peak heat release rate and total heat release for all of the full-scale tests.

As would be expected from examining the cone calorimeter curves in Figures 12-15, heat release rate curves predicted using the CBUF model and the cone calorimeter data for each of the four incident heat fluxes were similar in shape. Consistent with the trends in the cone calorimeter data for different incident heat flux values, the full-scale heat release rates predicted using the cone calorimeter data obtained at higher incident heat fluxes increased more rapidly than curves predicted using data gathered at the lower heat fluxes. The full-scale heat release rate curves predicted using the higher incident heat flux data also decreased more rapidly during the decay phase than the curves predicted using the lower incident heat flux data.

In general, the CBUF model was able to predict the heat release rate curves reasonably well for the full-scale tests conducted in this study. The model was able to predict the major features in practically all of the full-scale curves (e.g., major peaks), but had more difficulty in predicting some of the minor features in the full-scale data (e.g., some of the smaller peaks in the edge ignition curves in Figures 26-30). In some cases, the predicted heat release rate curves included additional small peaks that were not present in the experimental curves (e.g. the decay phase in Figure 26). These were partially due to the flickering flame front observed during portions of some of the tests, and the resulting effect on the measured flame area (e.g., E3-1 in Figure 19). One important point to note is that in this implementation of the CBUF model, the flame area was assumed to remain constant once it reached its maximum value (Figures 18-20). As a result, the burning out of individual elemental areas in the full-scale specimen is assumed to be taken care of through the decay of the heat release rate density curve measured in the cone calorimeter.

In general, the CBUF model was able to predict heat release rates more accurately for the thinner foams than the thicker foams. This would be expected as the thinner foams would more closely resemble the lining materials for which the CBUF model was originally developed. Further, it was observed in one of the earlier studies that the rate of flame spread in the vertical direction was different in the cone and furniture calorimeter tests [14] and no account is made here for such differences. Finally and as noted earlier, the flame area measurement technique used in this study did not account for the area on the sides of the specimen, which was more significant for the thicker specimens.

In general, the CBUF model did a better job of predicting results of edge ignition tests than of predicting results of center ignition tests. In particular, the ability of the model to predict the decay phase of the fire was much better for the edge ignition tests than the centre ignition tests. For the centre ignition tests, the growth phase was predicted well using heat release rate densities obtained with lower values of incident heat flux; however, the decay phase was only successfully predicted for the thinnest foam independent of the value of heat release rate density used. In the case of edge ignition, with the exception of the EE4 series, the entire predicted heat release rate curves were close to those measured in the full-scale tests.

The heat release rate curves in Figures 21-30 generally had a point of inflection 80-120 s after ignition of the slab (e.g., after approximately 85 s in Figure 23). Such a point of inflection generally indicates a change in the burning behaviour of the foam; in the present data, it corresponded in most tests to the time at which the flames reached the sides of the specimen. This is an aspect of the full-scale tests that is not directly represented in the present CBUF model, since as noted earlier, the flame area can significantly increase at this point when burning begins to take place along the edges as well as on the top surface of the test specimen. This, in part, explains why the present implementation of the CBUF model had difficulty in simulating the latter stages of fire growth, as modifications to the flame spread model would be required to account for the additional flame area observed in the large scale tests.

Further examination of Figures 21-30 indicates that heat release rate curves predicted using cone calorimeter data gathered at the lower incident heat fluxes (25-35 kW/m^2) were generally in better agreement with the experimental curves for tests of all but the largest foam specimens (C4, CC4, E4, EE4). This is well aligned with the incident heat flux of 35 kW/m^2 that was used to determine input values of heat release rate density for use in Equations (1) and (2) in the CBUF model. For the larger foam specimens ignited at the edge (E4, EE4), however, predictions made using data generated at 75 kW/m^2 appeared to best simulate the experimental data, while for those larger specimens ignited in the centre, predicted curves generated using an incident heat flux of 50 kW/m^2 (CC4) or 75 kW/m^2 (C4) were closest to the experimental data. These observations indicate that, although the CBUF model does show good potential to predict full-scale heat release rates, one important issue in applying the model to a given fire situation is again the choice of incident heat flux to use when gathering heat release rate density data from the cone calorimeter tests.

The importance of the incident heat flux used to obtain the input heat release rate density relates, at least in part, to the mode of burning of the foam specimens in the cone calorimeter tests versus that in the full scale tests. The agreement shown here suggests that the burning behaviour of these foams in the cone calorimeter is more similar to the burning of the foam slabs during the edge ignition full-scale tests than that exhibited in the centre ignition tests. Since an edge frame was not used (Figure 5) for the cone calorimeter tests, the boundary condition on the sides of the cone calorimeter specimens would be closer to the conditions encountered at full-scale with edge ignition, than to those at full-scale with centre ignition, where the burning foam is surrounded by an insulating layer of unburned foam for most of the test. Surface flame spread and pool fires were more pronounced in the center ignition tests, where a bowl was formed in the middle of the foam as the fire spread outwards from the center of the specimen. Those phenomena are not captured in cone calorimeter tests without an edge frame no matter what level of incident heat flux is applied.

Independent of how well the finer details of a given heat release rate curve are predicted by the CBUF model, one application of any scaling model might also be to simply predict peak heat release rate and time to this peak value, which may be specified by regulators. Tables 5 and 6, and Figure 31-32 indicate that for many of the tests in this study, peak heat release rate was best predicted using cone calorimeter data generated using a 50 or 75 kW/m^2 incident heat flux, with the exception of the centre ignition tests of the two thinnest foams. In all cases, the model over predicted the time to the peak heat release rate. As this time decreased with an increase in the incident heat flux used to generate the input data, times to peak heat release rate predicted using the data gathered at 75 kW/m^2 were closest to the experimental values, again underlining the importance of choice of incident flux when cone calorimeter data are used as input to fire scaling calculations

This research has been able to quantify the effects of the incident heat flux used in cone calorimeter tests on full-scale heat release rate predictions made using the cone calorimeter data in the CBUF model. The results of this study do not point to a single recommended incident heat flux that can be used for predicting full-scale results for flexible polyurethane foam, but indicate that the choice of incident heat flux for models may depend on geometry (surface area and thickness), ignition location and other key factors that influence the comparative modes of burning at small and large scale. Therefore, future research, in which heat flux measurements are made at the surface of the foam during full-scale tests, would be useful. Alternatively, heat fluxes could be estimated using theoretical models of flame front development. One of the other models developed during the CBUF project treated the flame on the mattress as a cylinder and calculated the heat transfer to the surface of the mattress, and resulting temperature increase in order to estimate flame spread and heat release rate [15]. Such a model would translate any differences in heights and diameters of flames observed in tests with different foam geometry or ignition locations to estimated heat fluxes ahead of the flames, and ultimately the incident heat fluxes used for testing in the cone calorimeter. Based on either the experimental or theoretical approach an appropriate incident heat flux could be recommended at least on a case-by-case basis.

A different approach might be to devise cone calorimeter experiments that more closely mimic the melting and pooling mode of burning. In testing thicker pieces of foam further consideration could be taken of the regression of the exposed surface of the foam and gradually increasing distance between the exposed surface and the cone heater. Foam regression and the changes in burning behavior that occur between the foam regression stage and subsequent pool fire stage have been discussed in detail by Kramer, et al. [20]. To begin to investigate this phenomenon for the thicker pieces of foam tested in this research, the foam regression rate was measured using video records of the cone calorimeter tests of the 10 cm foam specimens. Since the foam surface did not regress uniformly (e.g., Figure 33), the regression rate was measured at the centre of the front edge of the foam, as this location could generally be seen throughout the entire test, while the middle portion of the top surface was difficult to see during portions of the tests (e.g., when obscured by flame). The average regression rates at the measurement location were 0.31, 0.31, 0.33 and 0.38 cm/s for incident heat fluxes of 25, 35, 50 and 75 kW/m^2, respectively.

Foam regression will affect the incident heat flux from the cone heater to the exposed surface of the foam. To determine the effect of increasing the distance between the cone heater and foam, the incident heat flux was first set at 35 kW/m^2 using the Schmidt-Boelter heat flux gauge located at a distance of 2.5 cm below the cone heater. The distance between the cone heater and the heat flux gauge was then increased in 2.5 cm increments up to 12.5 cm, and the incident heat flux was measured at each of three locations along where the centerline of the specimen would be located. Figure 34 indicates that heat fluxes to the exposed surface will rapidly decrease due to foam regression. To put this heat flux data in perspective, at the time that the photograph in Figure 33 was taken, the middle portion of the exposed surface of this specimen would have regressed approximately 2.6 cm, increasing the distance between the heater and the exposed surface from 2.5 to 5.1 cm. The data in Figure 34 would indicate that the incident heat flux to the exposed surface at this point of the test would have decreased from the nominal value of 35 kW/m^2 to about 29 kW/m^2. This data also indicates that when the foam has collapsed completely and there is only a pool fire burning, the heat flux to the surface of the pool of melted foam would be approximately 12 kW/m^2. This change in incident heat flux should be taken into account when comparing cone calorimeter heat fluxes to those expected from flames in full-scale tests, as well as when selecting an appropriate incident heat flux to use in collecting cone calorimeter data for scaling models.

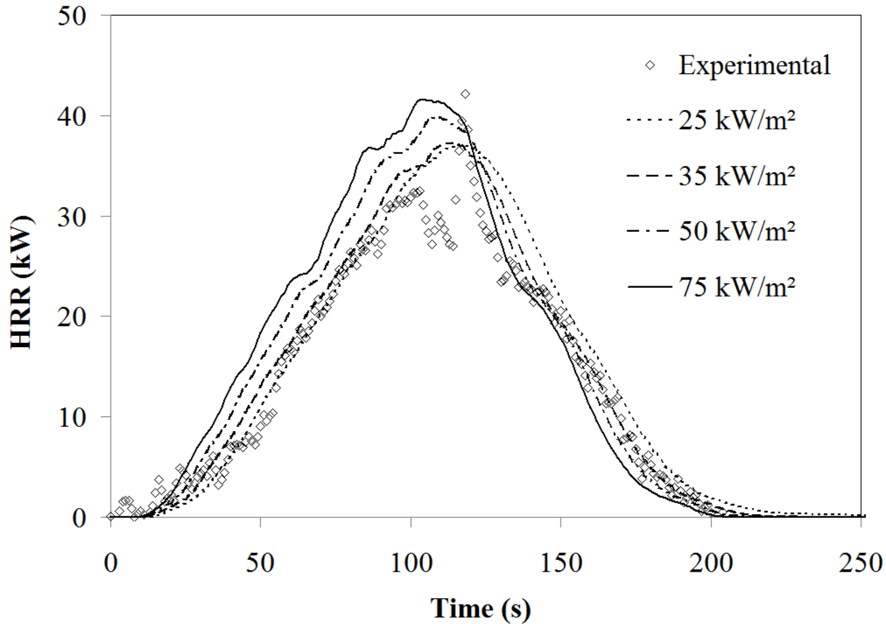


Figure 21. Comparison Between Heat Release Rates Predicted for Specimen C1-4 Using Cone Calorimeter Data Obtained Using Various Incident Heat Fluxes and Measurements Made During Furniture Calorimeter Tests (centre ignition).

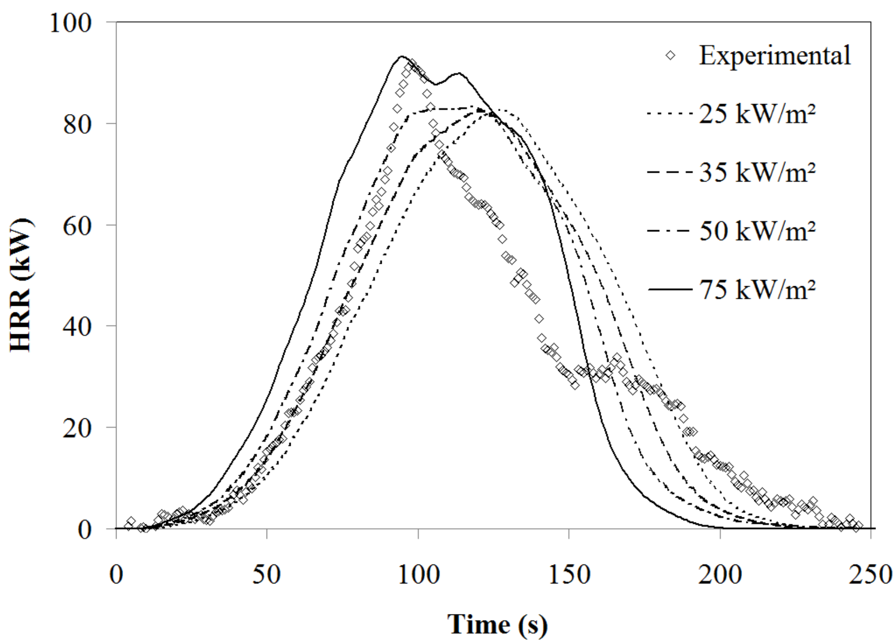


Figure 22. Comparison Between Heat Release Rates Predicted for Specimen C2-2 Using Cone Calorimeter Data Obtained Using Various Incident Heat Fluxes and Measurements Made During Furniture Calorimeter Tests (centre ignition).

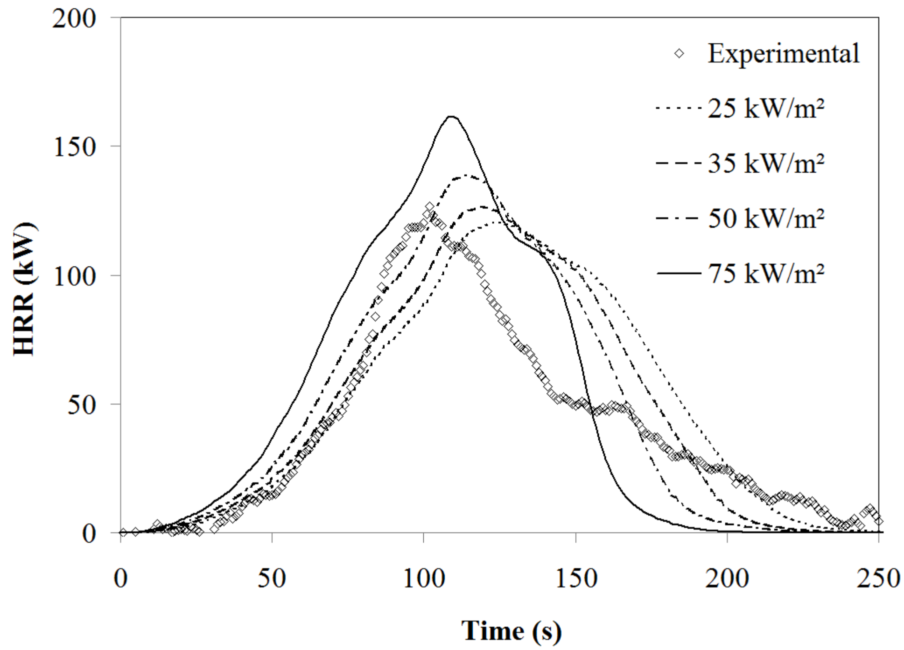


Figure 23. Comparison Between Heat Release Rates Predicted for Specimen C3-2 Using Cone Calorimeter Data Obtained Using Various Incident Heat Fluxes and Measurements Made During Furniture Calorimeter Tests (centre ignition).

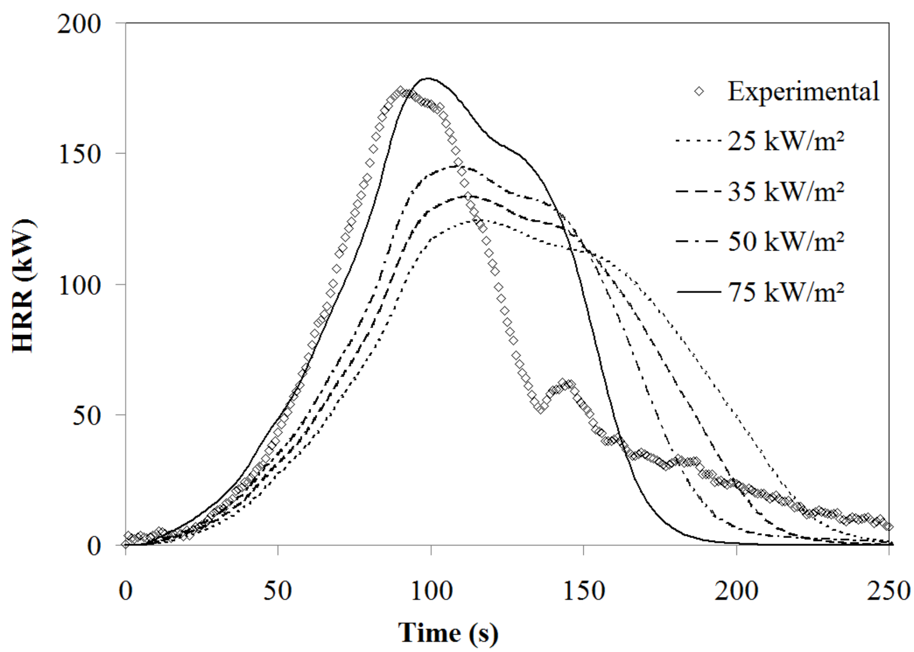


Figure 24. Comparison Between Heat Release Rates Predicted for Specimen C4-2 Using Cone Calorimeter Data Obtained Using Various Incident Heat Fluxes and Measurements Made During Furniture Calorimeter Tests (centre ignition).

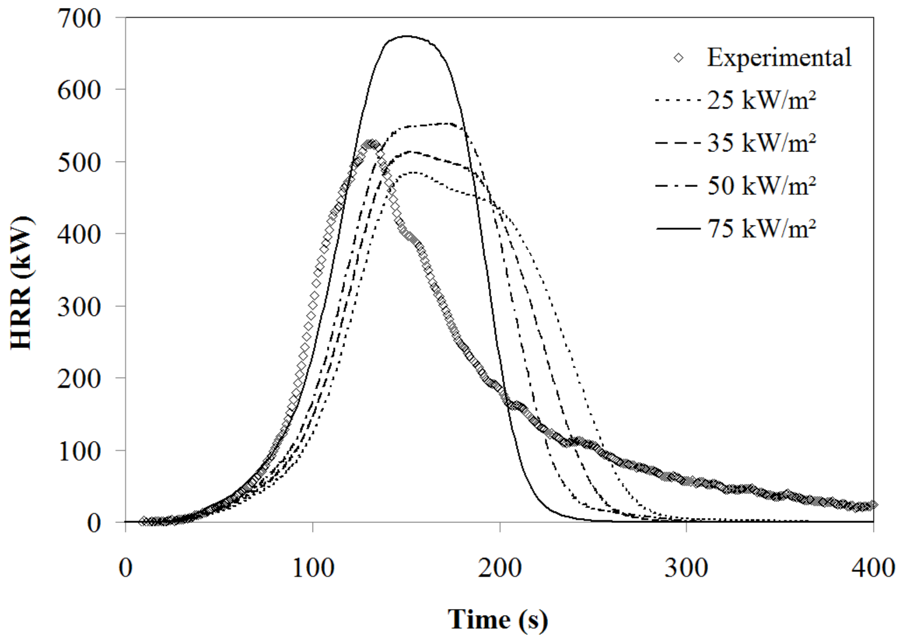


Figure 25. Comparison Between Heat Release Rates Predicted for Specimen CC4-2 Using Cone Calorimeter Data Obtained Using Various Incident Heat Fluxes and Measurements Made During Furniture Calorimeter Tests (centre ignition).

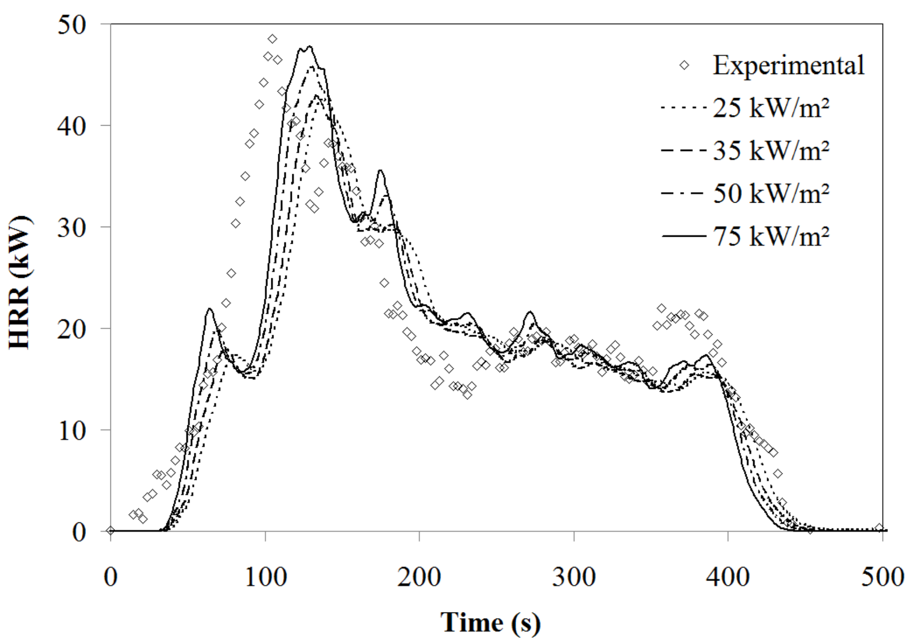


Figure 26. Comparison Between Heat Release Rates Predicted for Specimen E1-1 Using Cone Calorimeter Data Obtained Using Various Incident Heat Fluxes and Measurements Made During Furniture Calorimeter Tests (edge ignition).

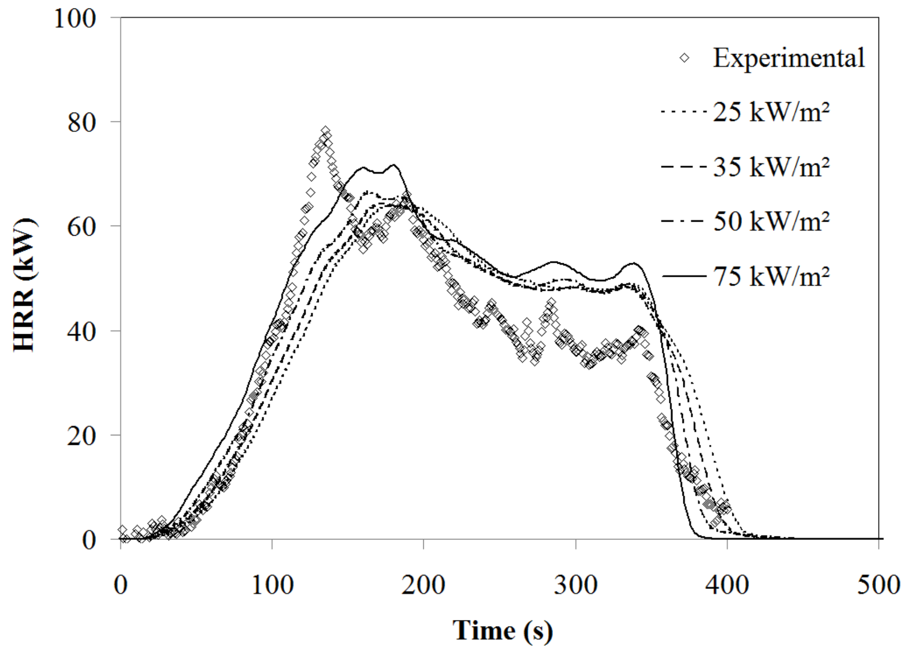


Figure 27. Comparison Between Heat Release Rates Predicted for Specimen E2-1 Using Cone Calorimeter Data Obtained Using Various Incident Heat Fluxes and Measurements Made During Furniture Calorimeter Tests (edge ignition).

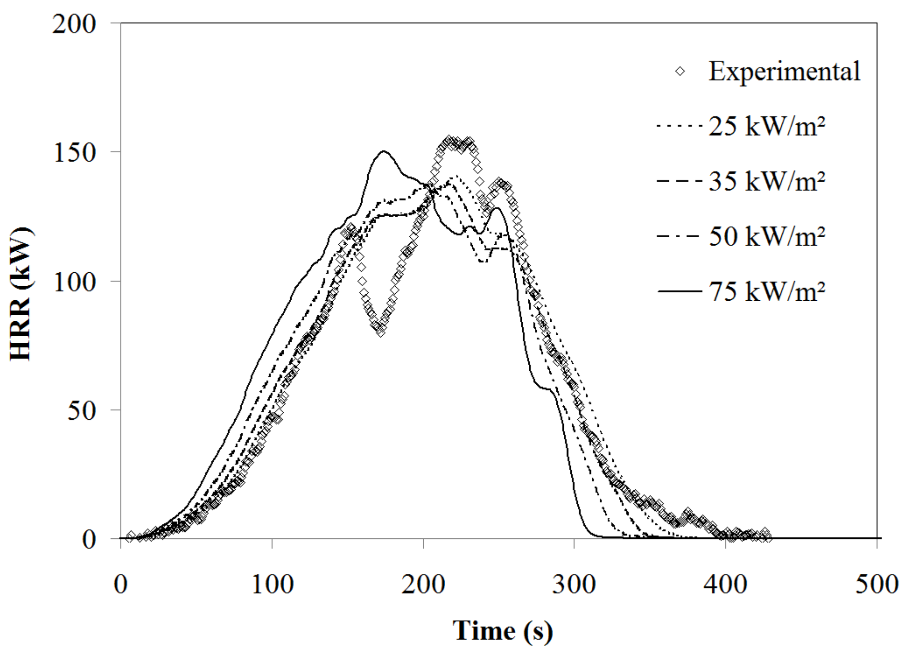


Figure 28. Comparison Between Heat Release Rates Predicted for Specimen E3-1 Using Cone Calorimeter Data Obtained Using Various Incident Heat Fluxes and Measurements Made During Furniture Calorimeter Tests (edge ignition).

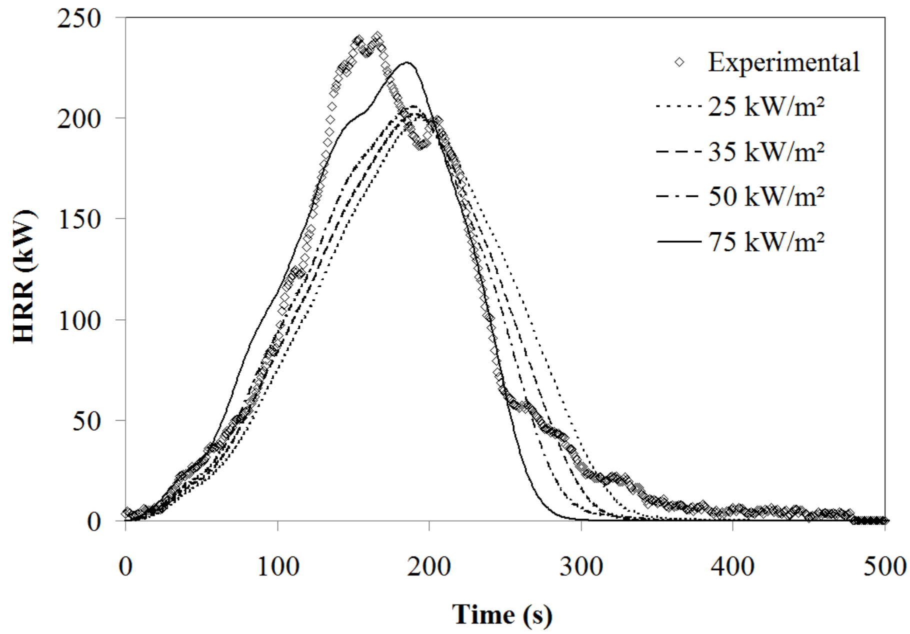


Figure 29. Comparison Between Heat Release Rates Predicted for Specimen E4-1 Using Cone Calorimeter Data Obtained Using Various Incident Heat Fluxes and Measurements Made During Furniture Calorimeter Tests (edge ignition).

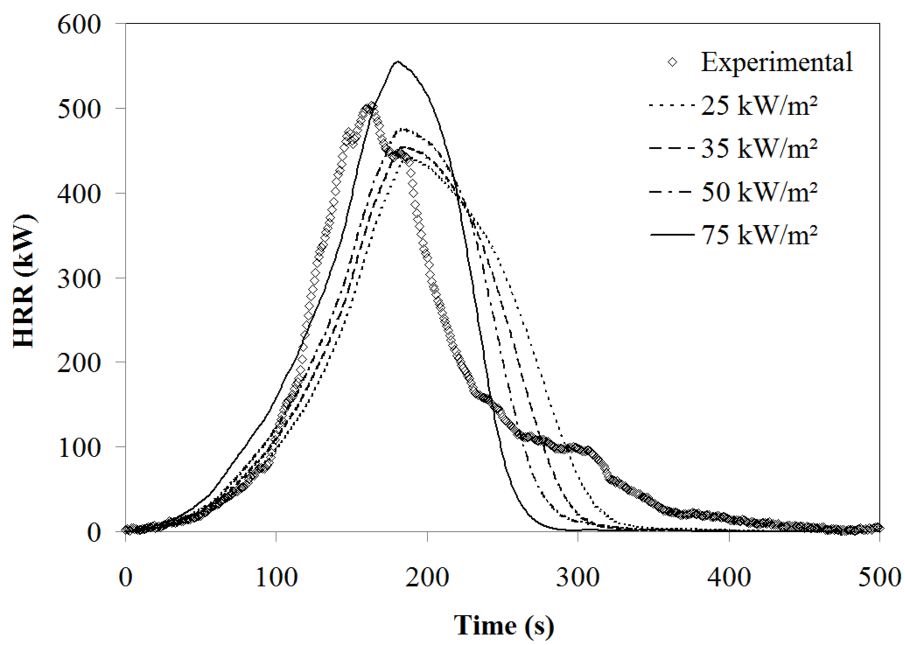


Figure 30. Comparison Between Heat Release Rates Predicted for Specimen EE4-1 Using Cone Calorimeter Data Obtained Using Various Incident Heat Fluxes and Measurements Made During Furniture Calorimeter Tests (edge ignition).

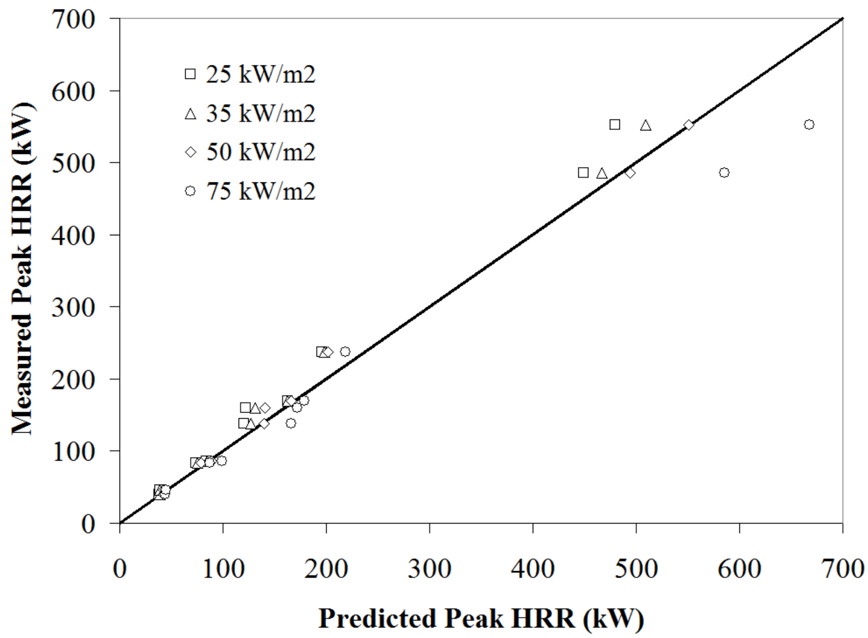


Figure 31. Comparison Between Peak Heat Release Rates Predicted Using Cone Calorimeter Data Obtained Using Various Incident Heat Fluxes and Measurements Made During Furniture Calorimeter Tests.

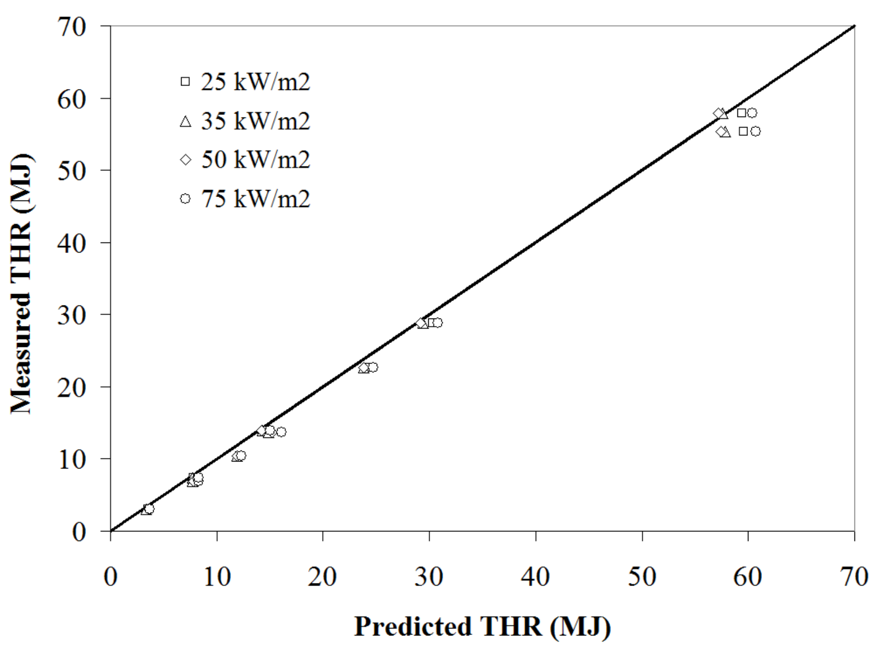


Figure 32. Comparison Between Total Heat Release Predicted Using Cone Calorimeter Data Obtained Using Various Incident Heat Fluxes and Measurements Made During Furniture Calorimeter Tests.

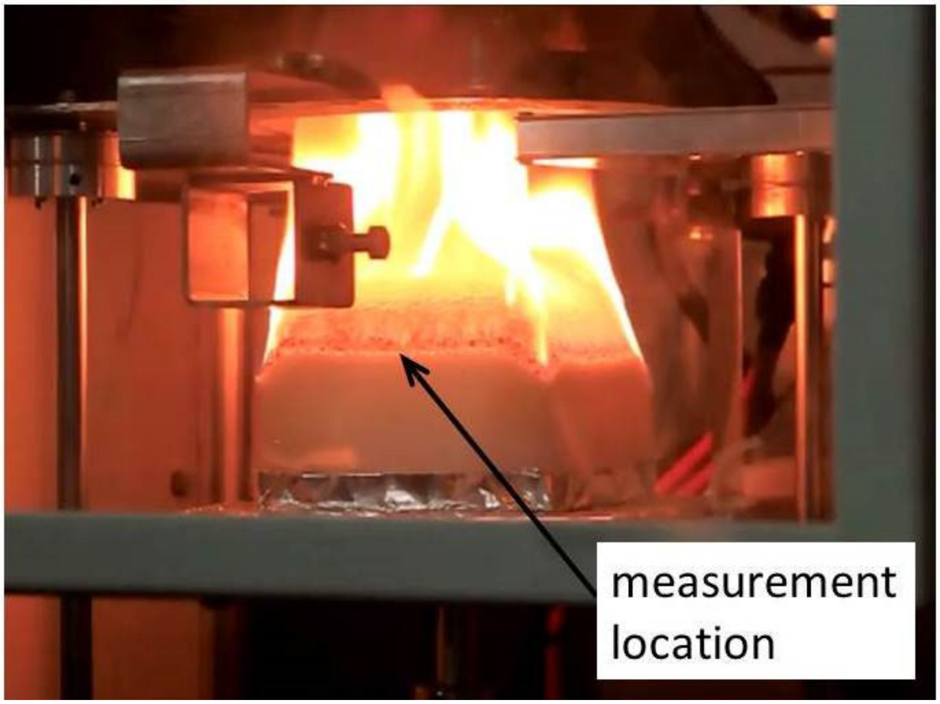


Figure 33. Photograph of 10 cm Thick Foam Specimen Approximately 15 s After Start of Cone Calorimeter Test Showing Variations in Regression of Exposed Surface (incident heat flux of 35 kW/m^2).

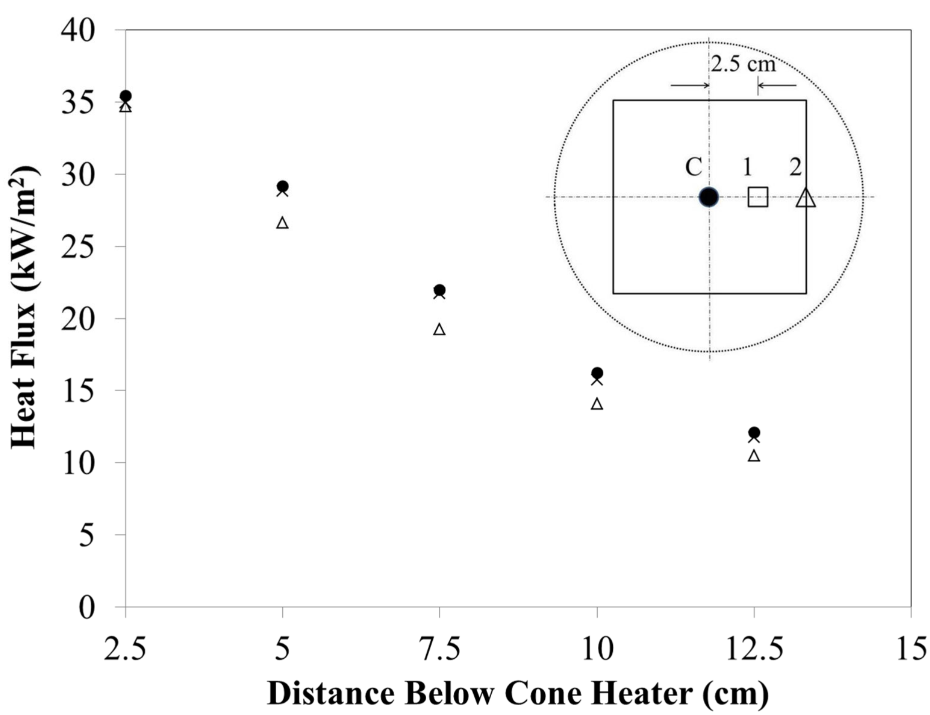


Figure 34. Effect of Increasing Distance From Cone Heater to Specimen on Incident Heat Flux for Three Locations Along Centre Line of Specimen.

Table 5. Comparison Between Heat Release Rate Predictions Made Using Cone Calorimeter Data Obtained using Various Incident Heat Fluxes and Measurements Made During Furniture Calorimeter Tests (centre ignition)

Test Series (Nominal Thickness)	Incident Heat Flux Used in Model (kW/m^2)	Peak HRR (kW) Ave.	Peak HRR (kW) (σ)	Time to Peak (s) Ave.	Time to Peak (s) (σ)	THR (MJ) Ave.	THR (MJ) (σ)
C1 (2.5 cm)	**Exp.**	**40**	(6.3)	**98**	(19.1)	**3.0**	(0.29)
	25	38	(6.3)	111	(13.6)	3.5	(0.04)
	35	39	(6.7)	107	(13.3)	3.4	(0.04)
	50	42	(7.7)	105	(11.4)	3.6	(0.04)
	75	44	(8.8)	102	(10.7)	3.7	(0.05)
C2 (5.0 cm)	**Exp.**	**86**	(8.3)	**94**	(8.4)	**6.9**	(0.14)
	25	84	(11.7)	123	(5.3)	**7.7**	(0.07)
	35	85	(13.7)	116	(6.4)	**7.7**	(0.07)
	50	89	(17.7)	112	(7.9)	7.8	(0.07)
	75	99	(20.8)	99	(9.0)	8.3	(0.07)
C3 (7.5 cm)	**Exp.**	**138**	(10.6)	**106**	(4.5)	**10.4**	(0.44)
	25	120	(1.2)	134	(13.1)	12.2	(0.02)
	35	127	(2.7)	127	(12.7)	11.9	(0.02)
	50	140	(4.7)	122	(11.8)	11.9	(0.02)
	75	166	(8.3)	117	(12.4)	12.3	(0.02)
C4 (10.0 cm)	**Exp.**	**160**	(21.6)	**97**	(10.7)	**13.9**	(0.94)
	25	122	(3.1)	125	(13.7)	14.8	(0.25)
	35	131	(4.1)	121	(13.1)	14.3	(0.24)
	50	141	(5.6)	119	(13.2)	14.2	(0.24)
	75	172	(8.7)	109	(14.8)	15.0	(0.25)
CC4 (10.0 cm)	**Exp.**	**552**	(51.9)	**127**	(5.7)	**55.3**	(3.45)
	25	480	(6.9)	157	(3.8)	59.6	(0.76)
	35	509	(4.4)	155	(4.7)	57.8	(0.73)
	50	551	(6.0)	168	(14.2)	57.4	(0.73)
	75	668	(6.8)	147	(3.8)	60.7	(0.77)

Table 6. Comparison Between Heat Release Rate Predictions Made Using Cone Calorimeter Data Obtained using Various Incident Heat Fluxes and Measurements Made During Furniture Calorimeter Tests (edge ignition)

Test Series (Nominal Thickness)	Incident Heat Flux Used in Model (kW/m^2)	Peak HRR (kW) Ave.	Peak HRR (kW) (σ)	Time to Peak (s) Ave.	Time to Peak (s) (σ)	THR (MJ) Ave.	THR (MJ) (σ)
E1 (2.5 cm)	**Exp.**	**46**	(10.0)	**99**	(6.0)	**7.4**	(1.01)
	25	39	(5.7)	139	(11.6)	7.8	(0.10)
	35	39	(5.2)	134	(10.0)	**7.7**	(0.10)
	50	42	(5.0)	128	(11.4)	8.1	(0.11)
	75	45	(5.0)	125	(11.5)	8.3	(0.11)
E2 (5.0 cm)	**Exp.**	**84**	(12.1)	**143**	(8.5)	**13.7**	(0.29)
	25	74	(13.3)	190	(7.6)	15.0	(0.12)
	35	75	(13.2)	182	(11.1)	14.9	(0.11)
	50	79	(14.9)	172	(12.7)	15.2	(0.11)
	75	87	(18.4)	172	(12.9)	16.1	(0.11)
E3 (7.5 cm)	**Exp.**	**169**	(13.7)	**188**	(27.2)	**22.7**	(1.23)
	25	163	(24.3)	208	(13.5)	24.4	(0.12)
	35	163	(26.2)	203	(13.5)	23.8	(0.12)
	50	166	(28.3)	196	(8.0)	23.8	(0.12)
	75	179	(31.4)	182	(9.3)	24.7	(0.12)
E4 (10.0 cm)	**Exp.**	**237**	(24.8)	**175**	(10.3)	**28.8**	(3.96)
	25	196	(6.7)	208	(13.5)	30.3	(0.14)
	35	198	(7.4)	203	(12.5)	29.4	(0.14)
	50	202	(8.4)	201	(12.0)	29.2	(0.13)
	75	219	(10.3)	196	(10.0)	30.8	(0.14)
EE4 (10.0 cm)	**Exp.**	**486**	(34.8)	**173**	(22.4)	**57.9**	(3.67)
	25	449	(8.0)	193	(10.3)	59.4	(0.92)
	35	467	(12.2)	190	(13.2)	57.6	(0.89)
	50	494	(17.1)	188	(13.6)	57.2	(0.88)
	75	586	(28.8)	182	(14.1)	60.4	(0.93)

5. CONCLUSIONS AND FUTURE WORK

A model developed during the CBUF program was investigated for use in predicting full-scale fire behaviour of polyurethane foams based on heat release rate density data measured in the cone calorimeter and flame areas measured during full-scale fire tests. Cone calorimeter data was generated using four different incident heat fluxes and was applied to predict heat release rates for four different thickness of foam. The model did a better job of predicting furniture calorimeter results for thinner foams, as was expected, since it was originally developed for lining materials. The model had more success in predicting results in edge ignition tests than in center ignition tests, and in predicting results during the growth phase of the fire than during the decay phase of the fire. A single incident heat flux could not be recommended for use in cone calorimeter tests intended to generate heat release rate densities for input to the CBUF model for the range of tests outlined here. Instead the choice of incident heat flux appeared to depend on both the dimensions of the foam specimen and the ignition location.

While this evaluation of the CBUF model used flame area measurements from the same full-scale tests in which the heat release rates were measured, a model to predict time-dependent flame area is needed in order to practically implement the method for cases in which experimental data is not available. Such a model should take into account heat transfer both across the surface of the foam, as well as through the thickness of the foam, and for input rely only on small-scale test data. Once a flame area model has been successfully implemented in a predictive model for burning of foam slabs, the work will be extended to model fabric-covered solid-core mattresses and then to the development of correlations for other furnishings, including inner-spring mattresses. The model will further be refined to predict heat release rates and temperatures in room fire tests and actual building fires.

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